PROTOCOLS, FLOWS AND GLITCHES

Proceedings of the 22nd International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2017)

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Protocols, Flows and Glitches
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About CAADRIA

The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) promotes teaching and research in CAAD in Asia, and has members on six continents.

CAADRIA was founded in 1996 with the following objectives:

- To facilitate the dissemination of information about CAAD among Asian schools of architecture, planning, engineering, and building sciences.
- To encourage the exchange of staff, students, experience, courseware, and software among schools.
- To identify research and develop needs in CAAD education and to initiate collaboration to satisfy them.
- To promote research and teaching in CAAD that enhances creativity rather than production.

CAADRIA organizes among others an annual conference, the first of which was held in 1996 in Hong Kong. Since then, 21 conferences have been held in Australia, China, Hong Kong, India, Japan, Korea, Malaysia, Singapore, Taiwan, and Thailand. The 22nd conference, in 2017, will be held in Xi'an Jiaotong-Liverpool University, China. The conferences provide an opportunity for teachers, students, researchers, and practitioners to meet each other and learn about the latest research in the field. The proceedings of the conferences are available both on line and in research libraries around the world.

CAADRIA is one of the four founding organizations of the International Journal of Architectural Computing (IJAC), and supervises one issue each year. IJAC is published by Multi-Science in both paper and electronic versions.

Hyunsoo Lee
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Conference Theme

Protocols, Flows and Glitches

Data structures and network protocols now integrate operations of entire industries, and digital workflows encompass virtually all stages of architectural production. Buildings and the processes they undergo are represented by digital building information models, which are shared across disciplines to generate options and support decisions before they are committed to built form.

Yet, there are limits to the reach of digital modelling and predictability. The tools and frameworks within which building information models are created and used, are themselves subject to constraints and forces similar to those that impede architectural production and maintenance, including technical glitches, noise, error, versioning and compatibility issues, limits to quantifiability, questions of cost effectiveness, incomplete "information", and challenges of interpretation and negotiation. The question arises whether more powerful tools resolve challenges, or whether, in doing so, they encourage us to venture deeper into territories where yet more challenges are encountered?

However, our field of computer-aided architectural design engages also that which cannot, or cannot yet, be readily described or modelled. We thus negotiate the reach of formal representation, deepening appreciations of human agency and creativity and laying foundations for industry-transforming technologies.

CAADRIA2017 features original high quality papers and posters presenting current computer-aided architectural design research in a general sense, accommodating a broad spectrum of approaches ranging from speculative, informal investigations to conventional scientific research, including but not limited to the following topics:

- Computational design research and education
- Computational design analysis
- Generative, algorithmic and evolutionary design
- Digital fabrication and construction
- Collaborative and collective design
- Design cognition
- Virtual/augmented reality and interactive environments
- Virtual architecture and city modelling
- Human-computer interaction
- Ubiquitous and mobile computing
- Practice-based and interdisciplinary computational design research
- Theory, philosophy and methodology of computational design research
- Simulation and Visualization
- Building Information Modelling

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Keynote Speakers

New Structures
Manfred Grohmann

Digital Regionalism
Philip F. Yuan

Digital Apparition in Contemporary Chinese Architecture
Weiguo Xu

In Search of Organized Complexity
Zhenfei Wang

New Structures

Manfred Grohmann
University of Kassel, Germany
Bollinger+Grohmann, Frankfurt, Germany

While the design and construction of complex projects has always been a challenge for architects and engineers, workflows have completely changed over the past decades with the introduction of advanced digital technologies. High quality architecture and innovative construction can only be ensured with an interdisciplinary and integral planning approach. Architecture and construction is always based on functional, mechanical and structural principles and requires depth of experience with materials, construction methods and technologies on the part of all involved actors. But to push the boundaries with new projects it also needs actors who are willing to develop and realise the new. Digital tools and methodologies allow us to leave behind tried and tested typologies and to design structures that are tailored to suit their specific function. Computer-aided design, calculation, optimization and at the end manufacturing all help with the efficient implementation of such projects across all scales. A variety of exemplary projects illustrate these new kinds of structures, such as the Hermes Rive Gauche (architects RDAI), the Sphere Deutsche Bank (architect Mario Bellini), the Hungerburgbahn (architect Zaha Hadid), the Rolex Learning Center (architects SANAA), and the European Central Bank (architects COOP Himmelb(l)au).

SPEAKER BIOGRAPHY

Prof. Grohmann holds a diploma degree in Civil Engineering from the Darmstadt Technical University. Since 1996 he has been Professor for Structural Design at Kassel University. Besides being guest professor at the Städelschule in Frankfurt and the ESA – École d'Architecture in Paris, he is furthermore since 2015 Honorary Professor at the University of Melbourne and the University of Nottingham. In 1983 Klaus Bollinger and Manfred Grohmann established the practice Bollinger+Grohmann, now located in Frankfurt am Main, Berlin, Vienna, Paris, Oslo, Melbourne, Berlin, Munich and Rome with around 150 employees. Both combine teaching at architecture schools with their practice. Bollinger+Grohmann combine a high level of interdisciplinary knowledge like architectural geometry, software development, material and fabrication technologies with engineering expertise. Their range of services includes structural and façade design, geometry development, building physics and sustainability. The field of work spans between the structural design of housing, office, commercial, exhibition and event facilities as well as classic civil engineering structures such as bridges, roofs and towers.

Digital Regionalism

Philip F. Yuan
College of Architecture and Urban Planning (CAUP) Tongji University, China
Archi-Union Architects and Fab-Union Intelligent Engineering Co. Ltd, China

During the past decades in China, as the widespread concerned about material, craftsmanship and regional culture, digital design and fabrication technology has been leading an important role in interpreting and indicating a computational regionalism. In the perspective of Performative Tectonics, traditional materials have been not only the driving force for architectural form-finding process, but also differentially reflect the material performance and fabrication as well. Rather than being passive elements, performative tectonics has become the basis aspect due to its real participation. Meanwhile, as the significant roles of architectural robots, "digital factory" has realized the innovation of traditional tectonics. Architecture industry is experiencing a promotion from "traditional craft" to "mass customization". From the low-tech construction of the "Silk Wall" project in 2010 to the project of "Chi She" with robotic fabrication in 2016, Philip F. Yuan has been exploring the theory and practice of Computational Regionalism.

SPEAKER BIOGRAPHY

Philip F. Yuan, born on 1971, has accomplished achievements on the research and discovery progress of Digital Design and Intelligent Construction area. In recent years, Philip F. Yuan was awarded a variety of educational and design prizes, including Winner of Feng Jizhong Architectural Education Award in 2013, Excellent guidance tutor of National Board of Architectural Accreditation, China & Institute of Architectural Education and Accreditation, Architectural Society of China, Winner of the Young Architect Award of Architectural Society of China in 2014, the Nomination Award in 2014 ARCASIA Award, the 2014 Wienerberger Brick Award, Shenzhen Biennale Popularity Award in 2015, Gold and Silver Prize of Architectural Design awarded by Architectural Society of China in 2016. Philip F. Yuan has published more than 120 academic theses and his architectural design projects on academic architectural journals and magazines like ARCHITECT , ARCHITECTURE DESIGN, ARCHITECTURAL VIVA, PLAN, DETAIL, SPACE, AREA, etc. He has written 7 books including Fabricating the Future, Scripting the Future, and From Diagrammatic Thinking to Digital Fabrication.

Digital Apparition in Contemporary Chinese Architecture

Weiguo Xu
Chair, School of Architecture, Tsinghua University, China

Although architects seek cultural value of architectural design in the background of Pragmatism in mass construction in China, the designs, however, couldn't get rid of the commercial and pragmatic essence, even if it is excellent works we thought. Another design phenomena seems not to attract enough attention, which is using new digital technologies for architectural design. As design result, these designs are absolutely not direct expression of the technology, but a kind of new ideological value of architecture. It includes the expression of human behaviour, mental sensation, environmental restrictions, new social requirements and so on. It appears like apparition in practical projects, also in research and teaching in China. And it is going to be a general trend that cannot be halted to infiltrate into different aspects of architecture and to create a future scenery of architecture. The speech will introduce the digital new architectures in China including project, research and teaching.

SPEAKER BIOGRAPHY

Xu Weiguo is Professor and Chair of Architecture at the School of Architecture, Tsinghua University, Director of the DADA, and a leading scholar and architect in digital design. He has published more than 100 papers and 14 books, including books (co-authored with Neil Leach) Fast Forward>>(2004); Emerging Talents, Emerging Technologies (2006); (Im)material Processes: New Digital Techniques for Architecture (2008); Machinic Processes (2010); Design Intelligence: Advanced Computational Research(2013); Digital Factory(2015); and Architecture/Non-Architecture (2006), Parametric Non-linear Architecture Design(2016); Digital Architecture Design Works(2016). Several of his research projects have been funded by the Natural Science Foundation of China. He has lectured worldwide, been visiting scholar at MIT in 2007, and taught in SCI-Arc and USC in 2011-2012. He has curated the DADA series of events in 2013, and co-curated the Architecture Biennial Beijing 2004, 2006, 2008 and 2010.

In Search of Organized Complexity

Zhenfei Wang
HDD_FUN, China

High technology design and low technology construction is the design philosophy of HHD_FUN, we believe smart design can achieve the complexity within short schedule and low budget. The keynote will illustrate this methodology through several built projects in different scale including architecture, interior, installation, product design and more.

SPEAKER BIOGRAPHY

Zhenfei Wang graduated from Berlage Institute in Rotterdam with an Advanced Master degree of architecture in 2007. He worked in UNStudio (Amsterdam). Before that, he gained his Bachelor degree of Architecture from Tianjin University. He founded HHD_FUN together with Luming Wang in 2008. Zhenfei Wang was awarded the third prize of the New Chinese Architecture at CA'ASI which held by Architecture Studio office and AREA magazine. As emerging architects, HHD_FUN were invited to participate in the 2019 Venice Biennale and the "Machinic Processes" Architecture Biennial Beijing 2010 (organised by Weiguo Xu and Neil Leach). HHD_FUN also won the "2015 Iconic Award" and "2016 German Design Award". As cross-over architects, HHD_FUN is keeping in close touch with artists, designers and engineers from various fields.

x

Foreword

The annual CAADRIA (Association for Computer-Aided Architectural Design Research in Asia) conference provides an international community of researchers and practitioners with a venue to exchange, to discuss and to publish their latest ideas and accomplishments. This volume contains the 87 research papers that were accepted for presentation at the 22nd International CAADRIA Conference, hosted and organised by the Department of Architecture at Xi'an Jiaotong-Liverpool University in China. The contained papers can be obtained digitally from CUMINCAD.

This volume is the outcome of an extensive collaborative effort of a team of volunteers, and it marks another year of growing quality and strength in the history of CAADRIA. Calls for papers in August of 2017 resulted in the submission of 190 abstracts. These were initially blind reviewed by the paper selection committee, which invited 171 abstracts for further development. Of these, 117 full papers were submitted to the full paper review stage. A team of 138 international reviewers assist us in the full review stage. Three international reviewers carried out a double-blind review of each submitted paper. Following the reviewers' recommendations, 86 papers were finally accepted for publication.

We congratulate the authors for their accomplishment. Next to the authors, the reviewers, who volunteered valuable time and effort, deserve our sincere thanks and acknowledgements. We sincerely thank the organising team at Xi'an Jiaotong-Liverpool University, in particular Dr. Christiane Herr, conference chair. We would also like to extend a special thanks the ProceeDings team – Gabriel Wurzer and Wolfgang Lorenz – for their relentless support with customizing the system to the needs of this CAADRIA Proceedings.

On the following pages, we acknowledge and thank those who contributed to the production of this volume. In closing, we sincerely thank the CAADRIA community for offering us the honour to serve as members of the paper selection committee for CAADRIA 2017.

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Ye Zhang, *National University of Singapore, Singapore*

TABLE OF CONTENTS

About CAADRIA i

Conference Theme iii

Keynotes v

Foreword xi

Virtual Reality **11**

Digital Ephemera 13
Tane J. Moleta

Reimagining Braga 23
Fauzan Alfi Agirachman, Yo Ozawa, Aswin Indraprastha, Michihiko Shinozaki, Irene Debora Meilisa Sitompul, Ruri Nuraeni, Augustine Nathania Chirstanti, Andrew Cokro Putra, Teresa Zefanya

3D Representations of Cities in Video Games as Designed 33
Danilo Di Mascio

A "Bounded Adoption'' Strategy and its Performance Evaluation of Virtual Reality Technologies Applied in Online Architectural Education 43
Chengyu Sun, Diqiong Xu, Kryvko Daria, Peihong Tao

Streamlining the Modelling to Virtual Reality Process 53
Lachlan Sharah, Erik Escalante, Alessandra Fabbri, Romain Guillot, M. Hank Haeusler

Gamification for User-Oriented Housing Design 63
Tian Tian Lo, Marc Aurel Schnabel, Tane J. Moleta

Augmented Reality **73**

Digital Construction 75
U-ichi Abe, Kensuke Hotta, Akito Hotta, Yosuke Takami, Hikaru Ikeda, Yasushi Ikeda

Integrating BIM, CFD and AR for Thermal Assessment of Indoor Greenery 85
Kazuki Yokoi, Tomohiro Fukuda, Nobuyoshi Yabuki, Ali Motamedi

Outdoor MarkerLess Augmented Reality 95
Munetoshi Miyake, Tomohiro Fukuda, Nobuyoshi Yabuki, Ali Motamedi

Campus Space Management Using a Mobile BIM-based Augmented Reality System 105
Seung Yeul Ji, Mi Kyoung Kim, Han Jong Jun

Design Tools **115**

Decoding Parametric Design Data 117
Immanuel Koh, Paul Keel, Jeffrey Huang

Understanding Cognitive Overload in Generative Design 127
Halil Erhan, Janelynn Chan, Gilbert Fung, Naghmi Shireen, Ivy Wang

Algorithmic-Based Analysis 137
António Leitão, Renata Castelo Branco, Carmo Cardoso

Establishing Parametric Relationships for Design Objects Through Tangible Interaction 147
Emad Al-Qattan, Wei Yan, Philip Galanter

Seat Selection System for Theatres and Concert Halls Based on Audio-Visual Integration Technology 157
Shuo Wang, Yuezhe Zhao, Shuoxian Wu

Design Process **167**

Agile X UniSA Pavilion: Agile Principles and the Parametric Paradox 169
Tim McGinley, Brett Abroe, David Kroll, Matt Murphy, Tessa Sare, Ning Gu

Challenges to the Adoption of BIM in the Chinese AEC Industries 179
Christiane M. Herr, Thomas Fischer

BIM and Public Administration 189
Juliano Pita, Marcelo Tramontano

Regional Barriers 199
Sining Wang, Kristof Crolla

Predictive Urban Analytics 209
Anycie Coorey, M. Hank Haeusler, Ben Coorey

Parametric and Generative Design **219**

Toward Temporal and Punctual Urban Redevelopment in Dynamic, Informal Contexts 221
Trevor Ryan Patt

Automatic 3D Modeling of Korean Traditional Architecture 231
Hyo Jung Lee, Hyunsoo Lee

The Mathematical Logic Behind Lai Thai 241
Walaiporn Nakapan, Yee Kee Ku, Apiwat Pattanasirimongkol

Enabling Customer Choice in Housing 251
Renee Puusepp, Taavi Lõoke, Kaiko Kivi

Generating Urban Form 261
Ben Coorey, Anycie Coorey

Design Optimisation **271**

Optimising Human Comfort in Medium-density Housing via Daylight and Wind Simulation 273
Dominik Holzer

Opossum 283
Thomas Wortmann

A Multi-Objective Genetic Algorithm Framework for Earlier Phases of Architectural Design 293
Serkan Kocabay, Sema Alaçam

Evolutionary Urbanism 303
Patrick Janssen

Speculative Urban Types 313
Theodoros Dounas, Benjamin Spaeth, Hao Wu, Chenke Zhang

Spatial Analysis **323**

Integration of Space Syntax into Agent-Based Pedestrian Simulation in Urban Open Space 325
Haojie Hu, Zixuan Luo, Yingnan Chen, Qiuyi Bian, Ziyu Tong

Measuring the Perceptive Intricacy of the Chinese Scholar Garden 335
Haofeng Wang, Christiane M. Herr

Generalizing Ekphrastic Expression 345
John S Gero

3D Visual Simulation and Numerical Measurement of Privacy in Traditional Korean Palace 355
Ji-Hyoun Hwang, Hyunsoo Lee

Investigating Visibility Properties in the Design of Aged-Care Facilities 365
Ju Hyun Lee, Michael J. Ostwald, Rongrong Yu

Performance-Based Design **375**

Breathable Walls 377
Negar Kalantar, Alireza Borhani

Optimization in the Architectural Practice 387
Judyta Maria Cichocka, Will Neil Browne, Edgar Rodriguez

Optimization of Window-Wall-Ratio using BIM-based Energy Simulation 397
Cheng Zhang, Lijing Ong

Empowering Urban Design Prototyping 407
Yufan Miao, Reinhard Koenig, Peter Buš, Mei-Chih Chang, Artem Chirkin, Lukas Treyer

A Parametric Analysis Process for Daylight Illuminance 417
Yi He, Marc Aurel Schnabel, Rong Chen, Ning Wang

Materiality **425**

Functionally Graded Architectural Detailing using Multi-Material Additive Manufacturing 427
Sawako Kaijima, Ying Yi Tan, Tat Lin Lee

Integrating Computational Design and Traditional Crafts 437
Jian Ming Huang

Bamboo Concrete Shells 445
Naoki Imanishi, Shinichiro Hinoki, Mizuki Muraoka, Ran Tateyama, U-ichi Abe, Hotta Kensuke, Yasushi Ikeda

Double-Curved Form Approximation with Identical Discrete Panel Geometries 457
Christoph Klemmt, Rajat Sodhi

SmartNodes Pavilion 467
Kristof Crolla, Nicholas Williams, Manuel Muehlbauer, Jane Burry

Shape Studies **477**

GrowMorph: Bacteria Growth Algorithm and Design 479
Saleh Kalantari, Mohammad Hassan Saleh Tabari

Topology-driven Form-finding 489
Seiichi Suzuki, Jan Knippers

Physarealm 499
Yidong Ma, Weiguo Xu

Generative Design Based on Sponge Spicules' Forms 509
Pengyu Zhang, Weiguo Xu, Weixin Huang, Yufeng Zhu, Rui Dai, Dan Luo

Interactive and Kinetic Architecture **519**

Prototyping Responsive Carrier-Component Envelopes 521
Andrei Smolik, Tengwen Chang, Sambit Datta

Human-Computer Interaction in the Form-Making Process 529
Saleh Kalantari, Ebrahim Poustinchi, Nooshin Ahmadi

Asymmetrical Double-Notch Connection System in Planar Reciprocal Frame Structures 539
Rebekah Araullo, M. Hank Haeusler

Computational Aesthetics **549**

The Other Digital 551
Matthew Austin

Digital Tools, Analogue Minds 561
Aleksandra Raonic, Milos Raonic

A Productive Ambiguity 571
Linda Matthews, Gavin Perin

Cognition and Evaluation of Architecture Environments Based on Geometric Contour References and Aesthetic Judgements 581
Miguel Carreiro, Marina A. P. Andrade, Miguel Sales Dias

Glitch Space 591
Blaire Haslop, Marc Aurel Schnabel, Serdar Aydin

Building Information Modelling 601

BIM-Supported Visual Language to Define Building Design Regulations 603
Hayan Kim, Jin-Kook Lee, Jaeyoung Shin, Jungsik Choi

Collaborative Algorithmic-based Building Information Modelling 613
Sofia Feist, Bruno Ferreira, António Leitão

Green Standard for Energy and Environmental Design 623
Yong-Ju Lee, Mi-Kyoung Kim, Han-Jong Jun

Integration of an Algorithmic BIM Approach in a Traditional Architecture Studio 633
Inês Caetano, António Leitão

Where am I? 643
Antony Pelosi

Digtal Scanning and Point Cloud Modelling 653

Construction Site Monitoring Using UAV Oblique Photogrammetry and BIM Technologies 655
Tengteng Qu, Wei Zang, Zhenwei Peng, Jun Liu, Weiwei Li, Yun Zhu, Bin Zhang, Yongsheng Wang

Applications of Integrated Digital Technologies for Surveying Tibetan Architectural Heritage 663
Zheng Sun, Yong Kang Cao

A Proposal for Building Safety Diagnosis Processes using BIM-based Reverse Engineering Technology 673
Hyejin Park, Seunghyun Lee, Eonyong Kim, Seungyeon Choo

Big Data **683**

Data Mining Tourism Patterns 685
Nai Chun Chen, Jenny Xie, Phil Tinn, Luis Alonso, Takehiko Nagakura, Kent Larson

Urban Autopoiesis 695
Peter Buš, Lukas Treyer, Gerhard Schmitt

Familiar and Unfamiliar Data Sets in Sustainable Urban Planning 705
Yuezhong Liu, Rudi Stouffs

Urban Pinboard 715
Madeleine Johanson, Nazmul Khan, Rob Asher, Andrew Butler, M. Hank Haeusler

Fracam 725
Gabriel Wurzer, Wolfgang Lorenz

Efficacy of Localization Through Magnets Embedded in Infrastructure 735
Mathew Schwartz, Andrzej Zarzycki

Spatial-Temporal Behavior Analysis Using Big Data Acquired by Wi-Fi Indoor Positioning System 745
Weixin Huang, Yuming Lin, Mingbo Wu

Digital Fabrication **755**

ProjecTables 757
Troels A. Rasmussen, Timothy R. Merritt

A Simple Fabrication System for Unfolding Complex Architectural Surfaces 767
Negar Kalantar, Alireza Borhani, Ergun Akleman

Application of Digital Fabrication Techniques to Reconstruct Ancient Machinery 777
Zi-Ru Chen, Kai-Hsiang Liang

Waterjet and Wire-cutting Workflows in Stereotomic Practice 787
Shayani Fernando, Dagmar Reinhardt, Simon Weir

Tools as Agents in Design and Making Processes 799
Paul Loh, David Leggett

3D Printing **809**

Soft Systems 811
Rachel Dickey

Small 3D Printers / Large Scale Artifacts 821
Stylianos Dritsas, Lujie Chen, Lawrence Sass

Developing Composite Wood for 3D-Printing 831
Rachel Tan, Chin Kiat Sia, Yong Kiat Tee, Kendall Koh, Stylianos Dritsas

Furniture Design Using Custom-Optimised Structural Nodes 841
M. Hank Haeusler, Manuel Muehlbauer, Sascha Bohnenberger, Jane Burry

Robotics **851**

Randomness in Robotically Fabricated Micro-Acoustic Patterns 853
Dagmar Reinhardt, Densil Cabrera

Robotic Simulation of Textile as Concrete Reinforcement and Formwork 863
Xiao Lu, Theodoros Dounas, Benjamin Spaeth, Chitraj Bissoonauth, Isaac Galobardes

Robotic Variable Fabric Formwork 873
Xuyou Yang, Shawn Jyh Shen Koh, Paul Loh, David Leggett

Fabricating Without CAD Models 883
Hao Hua, Tingli Jia

10

Form-finding with Robotics 893
Tian Xia, Jing Lin Koh, Yutong Chen, Yi Qian Goh, Stylianos Dritsas

Virtual Reality

P. Janssen, P. Loh, A. Raonic, M. A. Schnabel (eds.), *Protocols, Flows and Glitches, Proceedings of the 22nd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2017*, 13-23. © 2017, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

DIGITAL EPHEMERA

Autonomous Real-Time Events in Virtual Environments

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Abstract. This paper proposes virtual spaces designed in Game Engines promote a form of inhabitant hyperactivity. Allowing quick navigation between distant spaces the Game Engine fosters an appreciation of movement over pause, which may be to the detriment of architectural visualisation. This paper presents a series of three case studies that explore the notion of Real-Time Streaming Data within RTVE to enrich and enhance Virtual Environments. This paper proposes the notion of 'Digital Ephemera' can help produce a more immersive virtual environment. Based on the examination of these case studies, the paper concludes on a motion that breaking down the inherent 'stillness' of traditional RTVE's can be avoided by developing an environment that taps into data streaming and monitoring services to enhance the inhabitant experience.

1. Introduction

The core concern here is that the CAAD community has placed a particular tool at its centre and that is the 'Computer'. While not attempting to deny how beneficial it has been to the wider field of Architecture, there seems to be in architecture a larger impression looming that this 'media' as in the products produced through computing, are removed from the real business of brick and mortar. The CAAD research community has, as have many other fields taken it upon themselves to explore the ways that the computer can be used to aid and influence Architectural Design. I think that this slightly removed concept, of RTVE in relation operates as some kind of aberration, where visualisation, or representation, uniquely linked, yet also exclusively abstracted and excluded from the key subject - that is 'Architecture'. Then, is RTVE (and possibly all representation) not a glitch to the discipline? If we to consider it was a glitch, we could then learn something from these glitches as we know that by being made aware of an abstraction, we indeed learn or at least are allowed to focus in on a truly important characteristic of architecture.

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1.1. POSITIONS ON PHOTOGRAPHY

The photograph is an interesting construction to study in the context of CAAD. Photography is an exceptionally powerful tool when undertaking a study of architecture. I doubt there will be a single person in the field who has visited more well known and significant buildings than they have explored and come to know through the viewing of photography. So inextricably connected to photography is Architecture that we see a very early use of photography used explicitly to record and map out buildings of cultural significance by the french government in the 19th.C. Such an exercise then allows us to consider the photograph have been offered considerable agency to replace, or at best stand proxy for buildings built from a physical material. Here then, we really find the interesting linkage to CAAD in that the photograph is wholly constructed through various apparatus and tools, and all in the aid of as Patrick Maynard states 'To effect marks upon a surface' (Maynard 1997, p. 37). These marks are also, made at distance to the building, and also consumed remotely. Such a fundamental activity of modern life, the viewing of remote spaces through photography offers, or perhaps persuades the viewer the feeling of an authentic experience. Indeed, the viewing of the photograph is made possible by suspending the image before the eyes and allowing the reflected light to enter our eyes. We look at the image of a building and consider we have seen it. It is very very difficult to distinguish in our mind's eye, what we have seen, and what we have seen through seeing photographs. Both activities are seeing, and both lead us to an understanding of material, form, space or otherwise. Here we find a startling reality in the field of architecture where the medium of photography is almost permitted to be consumed as if it was an architectural experience.

1.2. ON GAME DESIGN

Numerous researchers have espoused the charismatic inhabitation of space within games (Moleta 2016; Moloney 2005). MMORPG, FPS, Open World, Building Games and so on have now captured the attention of at least two generations since the late 70's and increasingly so in present society (Niche 2009). It is not hard to find a person who has not dedicated a whole afternoon, weekend or even month to working out the intricacies of a particular tile's environment. There is also the distinction that 'games' are designed to be engaging, or challenging and that is the driver key incubating their inhabitation. Conversely, there is a range of environments that simply permit inhabitation and allow some minor alterations. An exemplar of this type of 'game' is Mine-Craft. Games of this genre are termed 'Sand Box', which hints at a space to author and create forms or spaces. Mimicking childhood activity of exploring form making in a physical media, the motiva-

tion is the simple pleasure attained through 'building', destroying and re-building. There is also a degree of enjoyment of observing the works of others, this is also carried across in Mine-Craft, where a large portion of inhabitants occupies the digital environment by moving about the various spaces admiring the works of others. A virtual tourism of a sort, and not altogether different from exploring a remote city via google street view from abroad. If we were permitted, we might draw a connection to the construction of designed spaces made by others in the virtual in alignment to that of the built world. Both, the virtualization of the real world (representation of existing buildings), and the virtual world (creation of non-existing buildings) are able to be experienced by the same mechanisms (i.e. Sight, Computer Screen), drawing the distinction inhabitants behaviour between the real and the virtual into close proximity.

2. Case Study One: Photorealistic VR Space

The first body of work falls into the field of architectural visualisation in the exact map of the terminology. It is visual and highly so. The materials are all carefully prepared and photo mapped onto the digital model. The environment looks as real as any given photograph. The procedure undertaken first generates a terrain map using high-resolution GIS data to reveal a high-poly mesh. This is then downsampled to produce a more stable and navigable site model. Following this, (figure 1) a trip to the site is undertaken and photogrammetry is used to collate key geographic features, such as rock outcrops or headlands. These models are left as relatively expensive high-poly with their photo-resolution textures intact. The next stage incorporates soft foliage and high-resolution trees. As a New Zealand based body of research here we are at a small disadvantage given that stock tree genus are not native and look well out of place in this context so new tree architecture and leaf structure need to be 'generated'. Here the interesting point is the tree trunk, branches and so on are native to the application, but the bark and leaves are modified using photo mapping to ensure the species map the native flora perfectly. This characteristic exposes a certain embedded 'glitch' to the field where there are a great number of approximations, made to achieve what 'looks' like photorealism, as a way to border on reality (Moloney 2003). In the case of say, Tadao Ando's work, the buildings appear to be made of concrete, but they are in fact not a perfect map, but rather a skin that imitates concrete, but a concrete without reinforcing or a footing, quite simply because it is not needed. And again, it does operate as photography as it is paper thin without any internal mass.

The reality of this case study is that although is looks like photography, and indeed uses aspects of photography the visible content is entirely fabricated. The tree's leaves are created from many sampled images, but area arranged in a fashion that never existed, or never could exist anywhere except with the RTVE. In summary, the environment presented here, is designed to deceive, is appears a picture extracted from the real world, it is photographic, but it is not a photograph. Moreover, the wet concrete floor has an almost cold feel to it, and the low lighting depicts an almost serene stillness. However, while we have gained the ability to produce increasingly high-fidelity visual environments observation of how people inhabit these spaces reveals a potentially fatal flaw for designers. There is a

tendency to move as deep into the environment as quickly as possible. From an architectural perspective, this spells the death knolls for the project, a participant or inhabitant is typically less interested in the building than they are in satisfying a desire to move freely within the digital environment. It can also be observed that the larger and more detailed an environment is, the more likely a 'virtual visitor' is likely to venture off exploring the limits of the environment simply to see how large it is, then upon reaching the edge of a given environment, they feel the 'game' is complete. As a response to these observations, this research questions: How can we ensure that the RTVE is not a simple extension of traditional Architectural visualisation tools, and how can we ensure that it does not operate like an amusement park attraction?



Figure 1. Photorealistic RTVE. Rock, cement, glass and steel are presented to a degree of fidelity that borders on 'photographic - quality'.

3. Real-Time Virtual Engine (RTEV's)

The use of computing to help architects and designers visualise their designs prior to construction is undisputed. The CAAD community has undertaken numerous studies vouching for the capacity of 'real' and 'immersive' environments for nearly two decades within Real Time Virtual Engines (RTVE). Head mounted displays, and higher processing power has allowed for more expensive geometry, materials and shaders to be employed bringing us ever closer to the real world. However at the exact same time steps forward in this area have only rewarded us with increasingly deeper or more complex explorations of 'the uncanny valley'. In architecture and design, digital visualisations are almost prerequisite, they are certainly compelling, but as this paper argues at times unsuccessfully. Recent trends in digital design have seen an increase in 'photo-realistic' impressions of a building or space. While photo-realistic may satisfy descriptions of the form, shape or material it does little to help us understand how the building performs in a kinetic and

often dynamic natural environment, and by doing so true sense ‘immersion’ can never be achieved.

By contrast, the game industry achieves enviable level ‘immersion’ within highly dynamic environments that often forego ‘high-resolution’ or ‘photo-realistic’ representations. This research then questions how might the dynamic capabilities of game engines help produce a more immersive architectural VR environment. This paper identifies that ‘game environments’ hold the advantage through employing a narrative or series of tasks or goals facilitate the offsetting of a reliance on a closeness to reality and enmesh an inhabitant into the ‘game environment’. Architectural visualisation is an extension of hand drawn images, this has evolved into ‘stills’ and finally animation. These are all however based upon static images that may or may not be linked in the case of animation. VR has given designers the ability to walk freely within a virtual environment, and indeed change the angle of view with the quick turn of one’s head. However, unlike game environments, in most cases these environments are more akin to inhabiting a still image than inhabitation of a ‘virtual-reality’ that is changeable, dynamic and responds to our presence.

4. Case Study Two: GUI for Atmospheric Input

As mentioned in the previous case study, the ability to move through the simulated environment is paramount to the discipline of architecture. However, can we move beyond this and if so, what are the ways in which we can achieve such a proposal. This section discusses a suite of Architectural VR environments that employ customised tools to inform the VR space. In the second case (figure 2) study a ‘work bench’ has been developed for the UnrealEngine.



Figure 2. RTVE with GUI Tool Interface. This environment allows incremental changes to be made to the environment through adjusting a series of sliders located in the top left-hand corner of the screen. DOF, hue, tone and the speed of the environmental factors each participate significantly in the construction of the environment. .

This allows the designer to control the characteristics of the Air, Water, Clouds, Precipitation, Environmental Sound, Environmental Lighting, Movement, Animation, Colour, Density, Opacity, Depth of Field, Texture and Point of View via a set of GUI tools or key presses. The outcomes of this approach to design allowed for 'on the fly' alterations of the VR environments before allowing 'inhabitants' into the VR space. One of the issues with Architects using Game Engines for design is the high time investment required to produce and present work, only to find a small iterative change is needed and then find that the entire environment does not (for whatever reason) work anymore. One key finding from this exercise is that the development of GUI tools allowed for iterative and incremental changes to be made without recompiling or rendering out the environment again. Reports on the in environment GUI system can be found reported elsewhere (De Bono & Moleta 2016).

5. Case Study Three: Toward Digital Ephemera

The third stage of this case study the redirected the GUI inputs for a great number of the atmospheric controllers. Where this example differs from the previous case study is that it stretches beyond 'representation' or 'visualisation' and connects to 'live' data feeds to invoke an irregularity or autonomy for the environment. By organising the VR environment in this way, it starts to suggest an autonomous condition that is less 'designed' and more 'grown' to achieve a quality that is different each time inhabitants visit. To achieve this variable input the Yahoo weather API (Developer.Yahoo.Com n.d.) and the WUnderground API (WUnderground.APU n.d.) were used to control ten different nodes within the environment. In this final case study (figure 3), if the wind is strong, clouds move more quickly, grasses blow more vigorously. If the wind blew from the NE, the clouds, trees, and soft foliage would respond accordingly. Cloud cover factor was graded to articulate the density in the SkyBox of the environment. Opening the file and visiting at night produces an evening scene with the building being light with artificial lights. The sound is located to specific points in the environment allowing for a more delicate blend of a range of acoustic events.

6. Discussion

To date, one very significant wall has existed which prohibits a meaningful inhabitation of space, and that is the condition termed 'uncanny valley' (Coyne & McLachlan 2005). A broad definition of this condition is a mapping of an environment or inhabitant that is 'close' to what we would experience through real vision. The largest shocks seem to occur whenever we encounter a natural subject, a tree, a human, and so on. While computing power and software tools have increased significantly, even within the past two years, this still seems to be a hurdle that cannot be breached. It is of note however that perhaps the uncanny valley is not a visual perception issue, but potentially an issue related to a lack of interaction between the 'self' and the other participants in an environment, or indeed environment itself. There are I suggest other demerits to VR Space. This is without doubt propensity to move 'quickly' through space. Perhaps this is a trained behaviour, whether one is to use WASD, a game console controller or the 'wand' for

HTC Vive of other, one of the greatest limitations to a meaningful inhabitation of space is this 'learned' behaviour to inhabitants virtual space at great speed. This occurs not only at the hands of skilled teenagers worldwide but any CAD operator who might guide a client or consultant through a BIM model at bullet speed. This is however slightly contrasting given that some of the greatest buildings are regarded to foster a thought provoking and sustained presence in a particular area of space (Zumthor 2006; Tanizaki 1977), such as Tadao Ando's Church of Light; Frank Lloyd Wrights- Fallingwater; Ludwig Mies van der Rohe - German Pavilion or Peter Zumthor's - Baths at Valls. Each very different buildings, but buildings none the less are typically heralded as structures of extremely refined elegance. It then asks the question? Would we consider such structures as significant if we were to experience them first hand via a segway at full speed that never permitted pause. Indeed, by the very nature of the RTVE that drives a great many of the virtual environments movement is accentuated, over pause.



Figure 3. RTVE employing weather API's.

If we were to imagine then, a more refined VR space, I believe it would be one where pause might gain an equal footing with movement, were an observation of a designed space might provide an inhabitant just a sampling of the characteristics we hold so dearly in architecture. If I were to unpack this condition a little more the RTVE or indeed 'Game Engine' was not designed for the architectural discipline. It is a toolset to allow the interactive media industry to produce games. By investigating games if only briefly we uncover fundamentally that each has a task set that encourages 'player' participation by moving either deeper into the environment to uncover increasingly difficult challenges or indeed amble deeper into a narrative. As technology has developed we have seen an increase in the visual ability of such tools develop rapidly, however, the basic structure remains largely unaltered.

If we return to the earlier statement, why do we accentuate movement over

pause in VR, I believe that it is due to the nature of our toolset inherited from the game or interactive media industry. Then how might we combat this in the terms and on the basis of the architectural discipline? I propose that we can achieve this through the notion of a 'digital ephemera'. Why would a digital ephemera aid a discipline so grounded in the real? The writings on atmosphere by Mark Wigley describe some of the tantalising and visceral characteristics of architecture. Sensuous and stirring gaseous and ever changing bodies of light, humidity, air pressure, and trajectories. Fading light, increasing levels of heat, reverberating acoustic events that shake and impart influence on the human body (Wigley 1998). Evoking the most exciting and bodily descriptors, architecture is now retrieving some of it's most wonderful characteristics. The 'ephemera' of Architecture is something that can never be captured in a fixed frame, and therefore the wonder of the discipline can indeed be more accurately described or even explored and embellished within a VR space. Do we need to develop new tools to achieve this, I believe not. Again, presently the most powerful tool we have is borrowed from another industry, and therefore it is likely very important to return to this industry to refigure or mine some of these moments of 'ephemeral' success.

- The sands of 'Journey' (That Game Company n.d.)
- The slow and fluid movement altered and buffered by the wind in 'Flower' (That Game Company n.d.)
- Humidity made palpable in 'Limbo' (PlayDead n.d.)
- The ever-changing acoustic environment of 'Child of Eden' (UbiSoft n.d.)

The above titles are a fairly eclectic set of references. None are particularly popular, and despite their high degree of craft, they fall cleanly into the 'indie' category. However, from an architectural perspective, each of these titles present something very important to the field of architectural design, if not something very 'desirable'. It is also of note that these are effectively quite slow experiences, a great change to many interactive environments is that the designers of these experiences have gone to great lengths to ensure that the inhabitant is allowed a considerably long term to inhabit these spaces. We have here, in an entirely different, but not altogether unrelated industry a set of examples of 'how to design a meaningful inhabitation' of space. This is outstandingly useful if we return to designing space in the virtual as we have now a reference to designing a structure as a static object in a fixed environment, but perhaps move toward a designed space within a much larger kinetic environment, or ecology if it were. The fleeting, cyclical, dissipating and retreating characterisation of the virtualisation of architecture may be improved greatly by considering the notion of ephemera. The terminology above mentioned, however, a 'digital ephemera' and again, this is as key as the current climate we design within is laced with computers, and by operating in this world we find the ability to connect again with the physical. SMARTCities, Wearable Tech, IoT, Smart-Spaces to name a few are increasingly allowing for greater transmission of data, and by doing so may indeed allow aspects of the real to feed back into the virtual world that we use to inform our designs.

7. Conclusion: Towards Real-Time Events in Architectural VR Environments

Where the RTVE can allow for the designer to control the outputs, or events in an organised manner, much like a film director, however one of the more interesting developments is the ability to tap into streaming data sources to place new inputs into the VR environment. What this allows is, similarly to a real environment, and indeed a MMORPG is a space that upon returning too, is entirely different. Perhaps, one of the deflating characteristics of many virtual environment is the simple characteristic that one visited, a repeat is not required, or indeed hinted at being a probability. While this is achievable through simple animated events, tapping into live data permits a more significant inhibition. What then are the benefits of virtual space and how do they impact upon the activities of design. Toward the beginning of this paper we ask, "do the virtual spaces we craft and form not bring about new understanding of architecture?" It is certainly a provocative question, and one with an answer that is only being touched upon. The first step to tackling this question is understanding the last half of the question, by defining, indeed, what is architecture. It is certainly a field that can be defined as the activity of designing forms and spaces, assembling materials in such ways as to influence inhabitation. In the loosest of definitions, this seems an acceptable fit. If we dig a tiny bit deeper, we uncover a world of CAAD, BIM, Generative Problem Solving, Advanced Manufacture which have all become inexplicably linked to the discipline, yet they support it, or refigure it in some way. I question then, architecture is perhaps a sound way to describe an approach to the creative activity of designing, or refiguring? Such a descriptor, as liberal as it sounds, however, is particularly powerful when located in relation to descriptions of space as found in VR environments. VR space allows and permits an inhabitant to be guided and altered in the way they inhabit space. Although architectural visualisation aims to represent the key characteristics of a particular building, we find that it often falls short due to the heavy visual basis many common tools employ. In this body of work, through the use of the RTVE a wider range of sensations are touched upon to simulate an environment with a higher degree of detail. The outcome does not focus solely on visual quality, but also on a rich, varied and kinetic environment.

The conclusion drawn from these examples is that when virtual inhabitants are presented with a greater variety of inputs, a significant change occurs in inhabitant behaviour. The inhabitant is less likely to explore the countryside, and will in most cases stand completely still in the environment - watching, listening and by great contrast, waiting to see what will eventuate in the space. Pausing between walls designed to focus a view, or simply observing clouds throwing shadows across a meadow are events that require patience and indeed a might indicate the success of a designer to guide their inhabitants activities within a space. This shift begins to signal a considerable culture shift in how an inhabitant begins to explore and come to understand a virtual space. The addition of relatively subtle details in these cases have countered the 'game-like' desire to race to the limits and instead are willing to wait long enough explore some of the characteristics that the discipline holds most highly.

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REIMAGINING BRAGA

Remodeling Bandung's Historical Colonial Streetscape in Virtual Reality

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Abstract. This paper presents the experience of the first phase of remodeling existing historical and colonial district in Bandung, Indonesia, including existing building façade, streetscape and street furniture. Braga Street is chosen as study case because it is a well-known historical street in Bandung with art deco style buildings constructed during Dutch colonial era. By remodeling it, it could help stakeholders to evaluate existing Braga street condition, to test any modification of buildings along the street and to determine specific regulation for the street. In this case, we use Unity3D and Oculus Rift DK2 for remodeling current situation. We gathered feedback from respondents using a questionnaire given after they experienced the model in VR. Many lessons learned from modeling process and respondents' feedback: higher frame rate to make seamless VR experience by having all components on a low poly model and provide smoother movement to prevent visual discomfort. This paper's conclusion gives suggestions for anyone who want to start architecture modeling in virtual reality for the very first time and how to optimize it.

Keywords. Virtual reality; historical building; digital reconstruction; streetscape.

1. Introduction

Virtual Reality (VR) is a generic term for technologies that artificially create an environment that encourages human sensory organs. VR technology projects the body of a user in a three-dimensional space and causes a sense of immersion in the space by the effect of the device by wearing it on his body part with images and sounds synthesised by the computer. In another way, VR is capable of shifting the user into a different environment without physically moving him (Gutiérrez et al. 2008).

As described by Whyte (2002), VR technology can be considered as a medium that has three defining characteristics: interactive, where users can interact with any projected models; spatial, where all models are represented in three spatial dimensions; and real-time, where all feedbacks received by the users from actions that occurred are given without noticeable pause. Also, to have something that we call as virtual reality experience, there are four key elements to be achieved: a virtual world, immersion, sensory feedback and interactivity (Craig & Sherman 2003). These characteristics show the possibility to use VR technology from built environment study, specifically for architecture. VR enables architect and professionals to dive into their design more realistic and feel the spatial experience before building the design. Not only to project design that is not constructed yet, but also to remodel existing buildings or architectural elements on selected parts of the city for digital reconstruction and preservation. In further, VR technology enhances collaboration among design team members (Wang 2007), including during early design stages in architecture design (Koutsabasis et al. 2012), which can make remote co-design team possible (Dorta et al. 2011).

In this paper, we share our experience on the first phase of remodelling building façade, selected construction and streetscape along Braga street in Bandung, Indonesia using VR. The first phase includes editing method for photos of buildings and street elements along the Braga Street and transforming them into a virtual reality model. Some students and faculty members are invited to experience the VR model and share their feedback on how to improve the model, using head-mounted display (HMD) as it is the best way to present the virtual world at life-sized scale and provides depth cues with stereoscopic vision (Ries 2011). Some challenges, difficulties, and solutions also will be discussed. The research was conducted by School of Architecture Planning and Policy Development of Institut Teknologi Bandung and College of Engineering and Design of Shibaura Institute of Technology.

The area we chose as our study case is Braga Street in Bandung, Indonesia. The reason to choose the street as the study case is that Braga Street has a unique streetscape in the form of art deco style buildings that Dutch colonial government built during their colonization in Indonesia. Most of the art deco style buildings were built around 1930. On our 3D model, we decide to model two buildings with a higher level of detail. They are Gedung Gas Negara or National Gas Building and Braga Permai. Both have architecture style and significant heritage value that represents the city development during the colonial era.

2. Research Goal

The overall research goal is to propose conservation and regeneration of the historic district, and existing heritage architecture in Braga Street. We adopt VR technology and examine how to make use of it and its effectiveness in an architectural documentation. On the first phase, the goal is to develop the first VR including building mass, façade, and some street elements and then, test it by asking students and academic staffs to experience the VR model using a head-mounted display and gathers their feedback on model precision and VR experience they have.

3. Research Methodology and Tools

This research use explorative (Groat & Wang 2002) qualitative research method (Creswell 2008). The exploratory qualitative study is conducted to gather data with various information possibility and at the same time, to know factors from information obtained. We use survey technique with a questionnaire as feedback collection method, and the analysis is done by several methods such as content analysis, distribution analysis, and correspondence analysis.

Before starting the modeling, we investigated research trends on visual simulation method, specifically on VR, and summarise the direction of space and landscape research that's already studied. We also explored Braga Street by investigated its tropical art deco style architecture, its current situation and its master plan until 2031. Hereafter, we initiate the development of VR space of Braga street and conduct a comparison experiment between the real world situation which people have experienced before and the VR space, and clarify the difference of impression between each environment with a questionnaire. By gathering feedback from the questionnaire, we can have a broad range of comments to evaluate which would give a more balanced evaluation of the model (Patel et al. 2002). In this research, we use Oculus Rift DK2 for head-mounted display, 3DS Max, SketchUp and Unity3D for 3D and VR modeling. On first phase, Unity3D is used only to prepare 3D models into VR mode. Further VR modeling using Unity3D is conducted in the next phase.

4. Modeling Process

The main data needed to start the modelling is pictures of all building elevations along Braga Street. Therefore, in the first phase, we had a survey to take photos of each building elevation on the east and the west side of Braga Street. Several tools were used, including digital camera, smartphone camera, and a tripod.

Before the survey, a briefing was conducted to divide the team members into two groups with different tasks. Each team oversaw photographing a row of buildings on each side of the road. There are two people on each team in charge of taking pictures of building elevations (one using the aid of a tripod), one person taking pictures of street furniture; one person is taking pictures of road along a sidewalk. Elevation pictures were taken in parallel and measured with water pass.

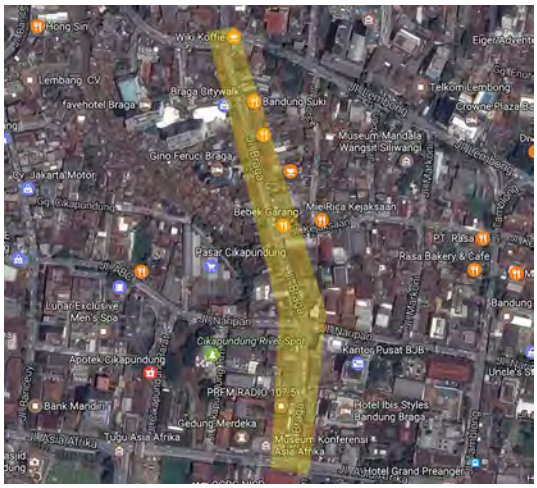


Figure 1. Braga Street. Source: Google Maps, 2016.

Pictures of street furniture which were taken during the survey, including chairs, bollards, lamp posts, flower tubs, street signs, and statues of the Braga letters. In this process, the team was also taking photos of the texture of the furniture. Also, the width of the pavement along Braga Street was also measured using the ceramic floor size as a reference while the Braga letter statues were documented using hand sketch method with a plan, size and height of the floor as their reference. The photographing process carried out from south to north, and it takes about three hours.

4.1. PHOTO CORRECTION

After completing the survey, the next step is photo correction. Before starting the process, all photos that have been taken had to be organized. There are two folders made which were corrected and uncorrected/raw folder. The raw folder contained all photos taken during the survey, while the corrected folder contained all photos that have been through correction process. All of them are saved in PSD and JPEG file format.

Photo correction is done by using Photoshop and briefly consisted of three main stages: perspective correction, photo cleaning (for building pictures and signpost photos which were covered with vehicles, people, trees, and street furniture), and texture extraction. At perspective correction stage, we use Transform Lens Correction feature and add some imaginary lines helping to keep the image straight. Furthermore, the photo-cleaning process is done to remove objects that block the buildings by using Stamp, cloning (copy & paste), and a little touch up (if required). Lastly, texture extraction is done to get pavement and street furniture texture.

4.2. 3D MODELING ON SKETCHUP

The modelling process is done with several applications as shown in figure 2. 3D modeling is done in five stages:

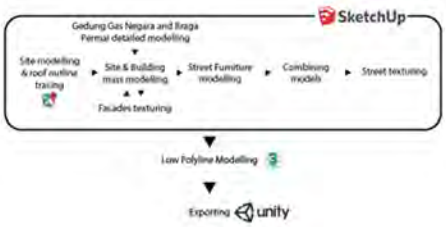


Figure 2. 3D modeling workflow.

a. Tracing

On tracing stage, the base model is created first to put the building models in exact position. We trace it from Google Maps images with several streets as boundaries.

b. Modeling

In this stage, the building models were created based on the base model which had been created before while the height of the models was made considering the proportion of the building's height and width as well as considering the buildings' proportion to Braga Street's width.

The modelling started with traced base model from Google Maps data that were taken on 2015. Pavement model was also based on the results of manual measurement, which was based on the pavement tile floor coverings. In exception, Gedung Gas Negara (GGN) and Braga Permai buildings that were modelled separately with higher detail.

c. Combining

The building models on the right, and the left side of Braga Street were inserted into the base model that had been made previously and using GGN model and Braga Permai model as reference. After placing building models along Braga Street, surrounding building mass models were also created to fill the void between Braga and other streets specified for the modeling. Upon completion of modeling the entire buildings along Braga Street and surrounding building mass models. then street furniture installation process was begun. After placing the street furniture, the pavement along Braga Street is also modeled and adding ceramic texture on top of the pavement design.

d. Texturing

After creating each building models, building elevation for each building is added as texture. We use building elevation photos that have been fixed previously on photo correction process. By adding photo texture, the models have to be modified again to match the height and width of the building in the photographs.

e. Exporting

Within the five stage of the modeling process, exporting to Unity 3D is done sev-

eral times to see if the modeling needs to be corrected, such as building height proportion from human eye level and checking whether buildings along Braga Street had been already modeled resembling the reality. During several trials of exporting to Unity 3D, several problems were encountered, for example, the loading time had been too long, and the process of importing into Unity 3D had become too heavy. Eventually, all the buildings in SketchUp models had to be exported to 3DS Max and then convert it into low polyline models. As for the street furniture models, they had to be remodeled in 3DS Max.

4.3. MODELLING RESULT ON UNITY3D

To create a VR space, we need to import modeling data created in SketchUp into Unity 3D. However, modeling data created in SketchUp was a high-poly model and could not be imported to Unity3D. Therefore, modeling data is remade into a low-poly model using 3DS Max. Detailed low-poly work stages are as follows.

a. Delete Unknown Objects & Combine Some Objects

3D model that was created in SketchUp have some unknown objects which are not displayed on the 3DS Max work area. Therefore, the unknown objects which were not supposed to be in the model are deleted. Separate objects can be combined by selecting the object that wants to be combined and convert it to an editable object.

b. Pro Optimizer Batch Processing

Pro Optimizer tool on 3DS Max is used to reduce the number of vertices and number of faces while maintaining the appearance of the object. Optimising the object makes it possible to lessen the amount of memory required for the scene, as well as simplifying modelling as it reduces the surface of the object. Also, the viewport display speed and rendering time are also improved. After every step had been completed, the models were exported over and over into the Unity 3D to check whether it has finally resembled the Braga Street what we know in the real world as shown in figure 3



Figure 3. VR model of Braga Street in Unity3D.

5. Feedback Collection

To collect the feedback on the first VR model we have created, we showed in an exhibition in March 2016 in ITB campus (figure 4) and ask visitor as a respondent to experience the model and give their feedback using survey technique in the form of a questionnaire. The questionnaire is provided after he experienced the VR space model using the head-mounted device. Respondents were asked for their experience of exploring in VR-version of Braga street (how immersive it is, nausea feeling and dizziness rate), comparing the familiarity with the real situation, comment, and feedback to the model. From 38 respondents, most respondents are college students with 68%, followed by high school students with 19% and lecturer with 14%.



Figure 4. Students are experiencing the VR model using HMD.

Questionnaire given to the respondent contains four questions that prepared qualitatively and quantitatively. Qualitative questions use open-ended structure, and quantitative questions use close-ended structure. In this paper, we are going to analyze text data from qualitative questions with the support of quantitative question result. Respondent was asked to describe their experience of exploring Braga Street as a VR model in their words. These questions were posed in the form of one open-ended question. They were also requested to rate the area familiarity, nausea feeling, and dizziness that occurred during experiencing VR model which were asked in the form of three close-ended questions.

6. Analysis and Interpretation

The first step of content analysis we do is open coding phase where we identify some keywords from text data we got from questionnaire results. Here's an example of respondent's answers on their opinion after experiencing Braga street as a VR model using head-mounted device,

"Exciting. The view looks almost similar to the real one, but I feel dizzy" (Student)

"It's almost like walking on Braga street, but with a different view" (Student)

Based on those answers, some keywords are found describing their experience on exploring VR model like "exciting," "view looks almost similar," and "feel dizzy." Then, axial coding is done to categorized those keywords we got from open coding phase into several categories. This phase is done to avoid a biased result. Table 1 is showing the result of axial coding process for the research.

Table 1. Axial coding result .

No	Category	Example keywords
1	Unfamiliar scene	Not familiar with the location
		It is like somewhere in Bandung
2	Uncomfortable	Too sensitive for me
		Feels uncomfort with the visual
3	Realistic view	It is like walking on Braga Street
		Almost similar to the original
4	Interested with the technology	Impressed
		Want to learn more about the app
5	Feeling dizzy	Too dizzy for me
		Feels dizzy when I walk too fast
6	Excited	It's fun
		Exciting

After we get all categories, distribution analysis is done to analyze the frequencies from each category. Distribution analysis is also done for the rest of quantitative questions that were asked during feedback collection process. The analysis is done to get to know dominance response about their experience on exploring Braga street as a VR model.

Figure 5 shows that 20 of 38 respondents feel excited when they are experiencing Braga street as a VR space model and 10 of 38 respondents think that the VR model they saw are realistic and close to the original scene, even though there are three respondents not familiar with the scene. Around seven respondents tell us that they are interested in the VR technology after experiencing it. Fewer respondents are feeling dizzy when they are in the VR scene and even feel uncomfortable.

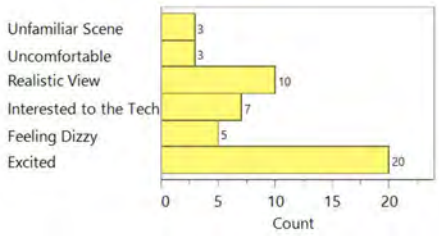


Figure 5. Distribution analysis on respondent feedback after experiencing VR modeling using HMD.

Based on distribution analysis on quantitative questions we asked those surveyed, as shown in figure 6 (left), 84% of respondents (3-4) are familiar with the scene they saw in the VR model. Only 17% of total respondents (1-2) are less familiar with the scene. For the nausea feeling rate, figure 6 (center) shows that 44% of total respondents (3-4) are having nausea-feeling during the experiment and 57% of those surveyed (1-2) are having less nausea-feeling. For dizziness,

figure 6 (right) shows that 68% of total respondents (3-4) are feeling dizzy during the experiment and 32% of them are feeling less dizzy.

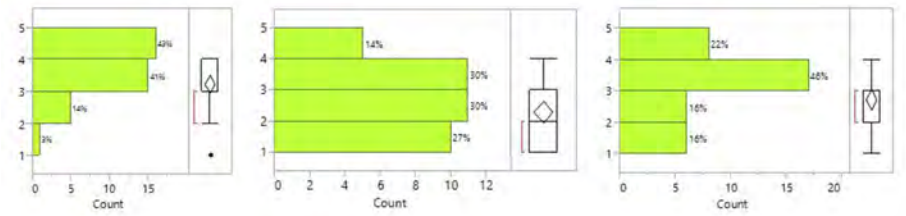


Figure 6. Distribution analysis on area familiarity (left), on nausea feeling rate (center), on dizziness rate (right).

The last phase we are doing from analysis process for this research is to do selective coding in the form of correspondence analysis. The analysis is done to know the correspondence relation between experience on exploring Braga street as a VR model and respondents' profession. Using this analysis, we can know what kind of experience that people will expect based on their profession. Correspondent analysis using ward hierarchical clustering can be seen in figure 7.

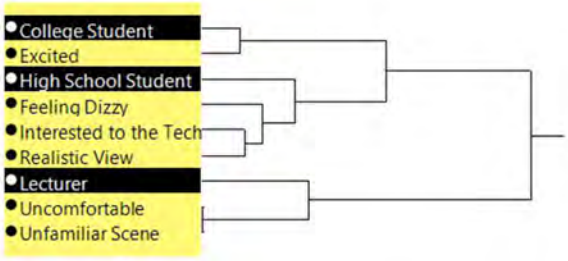


Figure 7. Correspondence analysis between respondent experience feedback and occupation.

We can see that most respondents who feel excited with the VR model are college students. For high school student, they are interested in the VR technology and feel that the scene is close to the real situation in Braga street, but most of them are feeling dizzy when entering the VR scene. For lecturer, they feel uncomfortable with having that kind of VR experience, and even they feel unfamiliar with the scene.

7. Conclusion

From this research, we learn on how to start architecture modeling in virtual reality for the very first time and how to optimize it. First, we need to decide which parts of buildings along the road that we want to model. Then, do the 1:1 building measurement to get the building size precisely and take lots of picture of buildings that wants to be modeled. Sometimes, the modeler needs to visit the site more

than once to take another picture or do another measurement to the building. On modeling part, it is recommended to use the latest CAD files from the government or related agency for site base model. It also makes the modeler easier to identify the buildings along the road. To create a detail, accurate and lightweight model, it is better to use professional 3D modeling software to avoid lots of triangulation in a model or even a surface and make it as light as possible.

Reflected from the model performance and questionnaire result, we can conclude that the VR model of Braga street needs to improve in several areas especially on increasing the rendering performance, better navigation and the level of details. 3D rendering performance could be enhanced by optimizing the mesh, reducing the triangulation and separating the area that should render at the same time and might increase the frame rate. The "Avatar" speed movement in VR world needs to be readjusted and to make it walk as smooth as how people walking in reality to achieve better navigation. The level of details is also needed to be increased by adding more depth and surface texture to the buildings to make the scene is more familiar to anyone to experience it on VR world. From the questionnaire, we can also conclude that most people are excited about VR technology and even interested in exploring it more especially for students. With current VR model and HMD device we use, nausea feeling and dizziness still can't be avoided by anyone who's experiencing VR world. VR model created in this research is a base model that can be used and improved for another future research.

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3D REPRESENTATIONS OF CITIES IN VIDEO GAMES AS DESIGNED

A Critical Overview and Systematization

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Abstract. The following paper proposes a way of reading and systematizing 3d representations of cities in video games. These representations are the result of a complex design problem not solely limited to 3d graphical representations. In fact, every 3d city is a designed artefact, an outcome of a design process that shares many common points with the architectural design process. Four main characteristics of 3d cities in videogames have been identified and described, namely: interaction/gameplay, narrative, architectural and urban representations, and graphical representations. The study of 3d cities in video games can also let us reflect on and improve our real cities. This piece of writing is part of a larger project that intends to investigate aspects of video games that can bring innovative approaches and theories into architecture and related fields. A further aim of the work is to raise interest and awareness on the topic and generate further discussions.

Keywords. 3d representations; 3d cities; video games; cities in video games; interaction.

1. Introduction

In recent years, video game theories, design, art and technologies have received increasing attention from academics and professionals working in many fields such as architecture, and this trend is ever rising. Several theories and tools common in architecture have been used as inspiration and methodologies in the video game's field and vice versa. Furthermore, real places and architecture always constitute an essential source of inspiration in the design of game environments such as the ones in *Half-Life2* (Valve 2004a). By contrast, architecture and related disciplines have always limited their interest to a small number of technical aspects of the video game world. In fact, there is a number - even if still quite limited - of academics and professionals that have used game engines for visualization purposes.

However, the potential of video games does not stand solely within the technological aspects. Concepts related to game design and the creation of artistic content - in particular stories and game environments - represent relevant fields of research in architecture. For example, Di Mascio (2010) showed how the game level design process and methodologies can have an educational value for architecture students and Zarzycki (2016) described the role of narrative space in creating immersive, evocative and compelling video game experiences. A publication titled *Space Time Play. Computer Games, Architecture and Urbanism* by (Von Borries et al 2007) presented general reflections on computer games, architecture and urbanism but in the form of short pieces of writing such as: short essays and statements, interviews and critical reviews of commercial titles. Nonetheless, these examples still represent a minority of studies. This situation may be due to several reasons. Video games are somehow still overlooked by academics that do not have the proper knowledge to handle them. The video game world is broad, complex, multifaceted, ever-growing and changing at a fast pace, so every scholar needs to be continuously updated. Furthermore, video games need to be played in order to be understood, studied and analyzed, and this is not an insignificant detail. To study a book, it is necessary to read it; to study a movie, it is necessary to watch it; and hence, to study a video game, it is necessary to play it (even if it would be better to say "to experience it"); it is impossible to study it through videos and images, because of video game's interactive nature that requires a more active participation. This research deals with 3d representations of cities in video games (a subject that can be significant in architecture for various reasons) from design to visualization. This topic is very wide, hence it is necessary to define some limitations. The paper focuses on 3d cities that can be found in commercial titles, hence the work does not analyze players' own creations in games such as *Minecraft* (Mojang 2011). However, city-building games such as *SimCity 4* (Maxis 2003) will be considered because, even if players can create their own cities, the representation of each 3d building has been carefully designed by professionals. Moreover, the piece of writing will deal only with one game mode: single player. The main objective of the paper is to give an overview of the topic and propose a first way to read and systematize 3d representations of cities in video games by selecting and describing their main aspects. Each aspect will be supported by the description of characteristics of 3d cities from various video games which have been directly experienced.

2. 3D Game Environments and 3D Cities in Video Games

Any video game must take place in specific virtual environments. Game-worlds constitute one of the most important aspects of the design process of a video game, as important as the design and creation of characters (Thompson et al 2007). At the beginning, game environments were just 2d pixelated representations that occupied only one single screen. First video games with smooth 3d scrolling graphics took place in indoor locations such as the dungeons in *Ultima Underworld* (Origin Systems and Electronic Arts 1992). Probably, the first video game that allowed the player to walk around a city using a smooth 3d real-time navigation system was *Legends of Valour* (U.S Gold and Strategic Simulations Inc 1992). However, in

this case the experience was also confined to one single, fantasy walled city whose complexity was limited by the available technology at that time. Technological advancements have allowed more and more complex game environments. Today's computer technology and digital tools allow game developers to design and build extremely complex and detailed 3d game environments, and for this reason game designers and artists are increasingly looking to architecture - the term is used here in a broad sense, including both indoor and outdoor buildings and spaces - as a source of inspiration, research and study in order to create their 3d virtual places. 3d cities have been exciting and evocative settings for many video games, and the interest in these virtual urban settings seems always very high. People's interest in the topic is demonstrated by the countless number of personal rankings of the best cities in video games that can be found on various websites. However, despite the broad number and variety of 3d representations of cities in video games, there is an almost total absence of publications that analyze and systematize them in a more structured way. For this reason, this research represents the first overview and way of systematizing 3d representations of cities in video games from an architectural point of view.

3. 3D Representations of Cities in Video Games as Designed Outcomes

3d cities have been represented in the video game media in several ways. Games such as *Half-Life2* (figure 1 - right), *Dishonored* (Arkane Studios 2012) (figure 1 - left), and *Bioshock* (2K Boston and 2K Australia 2007), all have their own cities or allow to build cities from scratch, such as in *SimCity 4*. However, after some gameplay sessions it becomes evident that their 3d representations are not simply addressed by pure aesthetical and/or technical purposes; there are several other aspects that should be considered such as: the game genre, the game storyline and the way the player interacts with the 3d virtual environment. Hence, there is enough evidence to say that 3d representations of cities in video games are the result of a complex design problem not solely limited to 3d graphic representation. In fact, every 3d city is a designed artefact, an outcome of a design process that shares many common points with the architectural design process. Every 3d city is the result of a creative process that starts with a conceptual design phase and finishes with the realization of the virtual 3d game environment. In the book titled *Half-Life2: Raising the Bar* (Valve 2004b) - that describes the making of the award-winning video game - an entire book chapter (Chapter 05 - Welcome to City 17) is dedicated to the description of the design process of the iconic *City 17*, the dystopian city where part of the game takes place. Unsurprisingly, the role of research of references before designing and building any element of the game-world is emphasized in the design of *City 17*: the designers photographed real locations during field trips, searched material on the internet and books (ibid). Research and analysis of architectural precedents, field trips and site analysis have always had - and still have - an essential role in the architectural design process. Furthermore, both design processes are iterative and driven by conceptual drawings. The final result in both disciplines should take into account various aspects including the functional, aesthetic and emotional ones.



Figure 1. In-game screenshots collected during the exploration of Dishonored's Dunwall (left) and Half-Life2's City 17 (right) (Image source: personal archive of the author).

4. Systematization of the Main Features of 3D Cities in Video Games

What are the elements that influence the design and 3d representation of cities in video games? A possible way of reading and systematizing the 3d representations of cities is represented by the identification, selection and description of the main features that, to some extent, influence their final appearance. Obviously, the 3d representation of a city in a video game is something very different compared to a 3d city model used for urban design and planning purposes. In fact, whilst the use of the city model in this latter field is often limited to the visualization of a planning or design proposal, the final appearance of a 3d model of a city in a video game is a product aiming at providing an interactive experience that, conceptually, can be compared only with a built project in the real world. For the purpose of this study, four main features have been identified and selected, namely: interaction/gameplay, narrative, architectural and urban representations, and graphical representations. It is important to underline that each of these four categories can influence the other in many ways and by following any order; their contours are not sharp but blended. This multilayered reading has been supported by the analysis of various sources (books, magazines, websites, videos, video games) and the author's experience in the fields of architecture and video games (both as a level designer and user). The game genre represents the first feature that characterizes a video game and it is one of the main elements that influences the 3d representations of cities and the way the player/user interacts with them. In fact, belonging to a specific game genre also influences the gameplay which is regulated by specific game mechanics.

5. Video Game Genre

Each game can be classified in genres in a similar way as movies or books. However, unlike movies and books, video games' genres are not strictly linked with their settings. For example, all video game genres can have - as a setting - a historical or modern city. Hence, it is evident that video games' genres are more connected with the experience that they can provide and the way it is provided. Generally, a video game can fit genres such as *FPS (First Person Shooter), role-playing, action adventure, strategy, and city-building game*. *Half-Life2* is an *FPS*, *Assassin's Creed* (Ubisoft 2007) an *action-adventure*, and *SimCity 4* a *city-building* game.

6. Interaction - Gameplay

The two words are strictly linked together because what the player can do, namely how he/she interacts with the 3d cities, defines the gameplay. The interaction/gameplay is heavily influenced by the game genre which is often connected with a specific point of view. The 3d representations of cities can be observed using three main points of view, namely: *first person*, *third person* (observing the character from a predefined distance), and views that can be defined as *god-like* - in games such as *SimCity 4* - because they do not follow a particular character but are aimed at monitoring and managing a big area (bird's eye). Another important element affecting the interaction/gameplay is the game-world structure. *Los Santos* in *GTA V* (Rockstar North 2013) is a good example of what is called *open world*, namely a game-world structure that allows the player to free roam around the city, and choose how and when to pursue specific missions. By contrast, a *linear-structure* constraints the player to explore limited areas that are similar to linear paths. In *Half-Life2* the player is constrained to exploring different parts of *City 17*, following a linear-structure, whilst in *Dishonored*, *Dunwall's* structure - although limited - allows a higher exploratory freedom because for each mission it is possible to move within an area of the city and its districts following different paths; this last game-world type can be called *semi-open world*. In city-building simulations such as *SimCity 4*, the creation of the city structure is part of the gameplay. All the above decisions are also affected by the kind of experience that the developers want to deliver to the player. Gameplay choices can be also influenced by the storyline; narrative permeates several aspects of a video game.

7. Narrative Layers: Plot, Background Setting and Main Setting

The concept of narrative in a video game is multifaceted and multi-scalar because it influences many different aspects of the game and hence it can be interpreted in many ways.

7.1. PLOT - STORYLINE

Every game has a plot/storyline that defines and justifies the player's mission and his/her actions. In *Mirror's Edge* (EA Dice 2008), the story is set in a dystopian city of the near future where everything is controlled by the government. The player plays a runner that, to avoid the surveillance, is forced to use the rooftops of buildings and all the elements that can be found in those areas such as ventilation shafts and backstairs. With this plot, it is evident that in *Mirror's Edge* the gameplay emphasizes a kind of stealth action, tactics and related use of spaces that are different from a video game that presents many openly gunfights such as in *Half-Life2*. This is why in *Mirror's Edge*, the rooftops of high-rise buildings are generally more detailed (figure 2 - right) than the urban environment located at the streets' level (figure 2 - left). With reference to 3d cities, it is possible to group, to some extent, the main narrative elements in two main layers: a first one that includes the elements that can be considered as part of the background; a second one that includes elements that define the main setting.



Figure 2. In-game screenshots collected during the exploration of City of Glass in Mirror's Edge. The urban environment located at the street's level (left) is less detailed than the rooftops of the high-rise buildings (right) where the main action takes place (Image source: personal archive of the author).

7.2. BACKGROUND SETTING

Usually, 3d cities are part of bigger settings that can be shown or only mentioned. Every game has (in a similar way to movies and novels) a background setting, namely a narrative (what) - that usually explains why the player is undertaking his/her quest -, a place (where) and a time (when) that serves as a frame for the main story. Also *city-building* games, such as *SimCity 4*, have their own settings. In general, a 3d city can be set in any time period - past, present and future - and any geographic location, both real and fictional (e.g. fantasy or sci-fi). The chosen place and time can be the theater of particular narrative events, such as the Third Crusade in *Assassin's Creed*; all those components create a big frame for the player's plot. In the publication titled *Dishonored: The Dunwall Archives* there is even a timeline that summarizes the main events of the world of *Dishonored* from -3000 until 1840 (Arkane Studios and Bethesda Softworks 2014). Sometimes, the 3d city itself can act as background setting and the player is allowed to explore only part of it. In *Half-Life2*, *Dishonored* and *Bioshock* we can only explore specific areas of *City 17*, *Dunwall* and *Rapture* but we can feel that those areas are part of bigger cities.

7.3. MAIN SETTING

All the elements that can be directly and closely experienced - visually and interactively - by the player can be considered to be the main setting. 3d cities - together with all their neighbourhoods and smaller areas such as alleys - are narrative virtual environments, because the way they are is the result of a series of previous fictional events that shaped the places in particular ways and the player can notice them during his/her explorations and actions. *Dunwall*, *Rapture*, *City of Glass* and *City 17* are designed and built upon stories. All these cities have a strong narrative embedded in every detail - buildings and streets show traces of past events - and this contributes to the players' immersion in realistic virtual cities. The idea of conveying narrative through the environment is also at the center of *environmental storytelling* (Smith and Worch 2010). However, architecture and places have always communicated, intentionally and unintentionally, stories and meanings.

8. Architectural and Urban Representations

All the features described in the previous paragraphs influence in a direct way the architectural and graphic representations of 3d cities in video games. Every 3d city is defined by an urban pattern, an architectural and urban representation, landmarks, and atmosphere, and all these elements can be graphically represented in several ways.

- *Urban pattern:* The urban pattern of the 3d cities in video games can be very diverse: a virtual counterpart of real cities - or at least portions of them - such as Manhattan in *The Amazing Spider-man* (Beenox 2012); fictional cities inspired by real places, such as *Los Santos (Los Angeles)* in *GTA V* or *Dishonored's Dunwall*, inspired by London; *Half-Life2's City 17* was influenced by the evolution of European Cities (Valve 2004b); completely fictional places located also in impossible locations such as the underwater city of *Rapture* in *Bioshock*.
- *Architectural style:* Architecture is becoming increasingly important in supporting gameplay, settings and storylines. Also architectural styles can be influenced by real places, such as the architecture in *GTA V's Los Santos* that are clearly inspired by the real Los Angeles. Architectural references (for example Victorian) from London and Edinburgh have being used to design *Dunwall's* buildings. Art Deco architecture has been represented in a detailed and fascinating way in *Bioshock's Rapture*. The dozens of buildings that appear in *SimCity 4* have been inspired by American architecture of different cities and states.
- *Landmarks:* Every city has its own distinctive buildings that can be easily recognized by the distance. As in reality, landmarks in 3d cities are visual narrative architectural elements useful for orientation, to communicate specific meanings, reinforce the setting, and instill wonder and curiosity. In addition, in many video games, the landmarks play an active role in the gameplay and allow further levels of interaction. For example, in *Assassin's Creed*, landmarks (such as towers and churches) are interactive distinctive features of the series. They can be climbed by the character and used as viewpoints to inspect the surroundings, orientate and admire the cityscape (figure 3).
- *Atmosphere:* Every virtual city is also designed with a character, an atmosphere that is influenced by the aspects previously described and other characteristics such as lighting and colours. The main aim of the atmosphere is to evoke emotions, increase immersion by creating a consistent and realistic world, and support a specific narrative. To achieve a mood, many concept sketches are produced at the beginning of each project, such as for *City 17* (Valve 2004b) and *Rapture* (Take-Two Interactive Software Inc 2008).



Figure 3. In-game screenshots collected during the exploration of cities in Assassin's Creed. Historical landmarks play an active role in the gameplay and allow further levels of interaction (Image source: personal archive of the author).

9. 3D Graphical Representations

All the previous design decisions related to gameplay, narrative and architecture affect the 3d graphical representation of the virtual cities. Digital modelling software (e.g. 3ds Max) and image editing packages (e.g. Adobe Photoshop) are the most diffused tools besides game level editors (e.g. Unreal Editor) in the creation of 3d cities. However, the same tools are being used to portrait 3d cities using very diverse 3d graphic styles. Nowadays, there is an increasing interest in creating more realistic and detailed environments. Nonetheless, 3d cities have a variable level of detail (closer to reality or diagrammatic) visually represented in a realistic way - for example using textures and shaders based on pictures of real materials - or in artistic styles inspired by: comic books and cartoons, such as in *SimCity 4* or *Kingdom of Amalur: Reckoning* (38 Studios and Big Huge Games 2012); illustrations and paintings, such as in *Dishonored* or Japanese anime style such as in *Tales of Xillia* (Namco Tales Studio 2013).

10. Final Diagram and Some Reflections

The table displayed below (figure 4) summarizes the main elements that address the representations of 3d cities in video games. It is evident that the graphic representations are tailored to interactive and narrative needs, hence these are used to support and strengthen the final interactive experience. As in any real-world design process, it is essential to have a final vision shaped by research and concept design. Furthermore, a study of 3d representations of cities in video games can also inspire alternative 3d visualizations for serious games in order to improve people's awareness of the urban environment (e.g. for participatory design activities). Digital technologies should always support the development of a meaningful architectural and urban vision, also in reality. Studying 3d cities in video games could also improve our way of designing real cities. Nowadays in the real world, there is an emphasis on big data, quantitative analysis and efficiency, concepts, for example, close to the smart city movement that misses interesting and human-scale visions. A city can be efficient but at the same time alienating, and the projects produced during the *Modern Movement* have already demonstrated all the limitations of these kind of approaches. It is not a case that many new cities that are being

built around the world from Asia to Africa miss character and "look all the same" (Greenfield 2016). Maybe architects can learn something from the handcrafted 3d cities in video games where qualitative aspects and meaningful experiences are the final aims. The idea that 3d cities in video games can positively influence the way we look and design real places is being also discussed on popular newspapers such as *The Guardian* (Hoad 2014) and this interest is supposed to grow, especially with the diffusion of *Virtual Reality (VR)* technologies and more complex game-worlds (that will include a better artificial intelligence).

Video Game Genre	FPS, action-adventure, city-building, etc.		
Gameplay/Interaction	Interactive actions: walk, run, jump, drive, talk, fight, etc.		
Player's point of view	First person point of view	Third person point of view	God-like view
Game-world structure	Open world	Semi-open world	Linear world
Narrative layers	Plot/storyline		
	Background setting	Narrative, Temporal, Geographical, Urban	
	Main setting	Cities, quarters, alleys	
Architectural and urban representation	Urban pattern, architectural style, landmarks, atmosphere		
Graphic Representation	Level of detail	Realistic or diagrammatic	
	Artistic style inspired by	Reality, comic books, cartoons, illustrations, paintings, Japanese anime, etc.	

Figure 4. Summary of the main elements influencing the 3d representations of cities in video games (Table source: personal archive of the author).

11. Conclusions and Future Developments

This paper dealt with 3d representations of cities in video games, and identified, described and proposed a set of concepts that can provide a way of reading and systematizing them. Despite the increasing economic, cultural, artistic, social and technological importance of video games, scholars in the architecture field are still limiting their research to game technologies applied to general visualization purposes. The main aspects that define 3d representations of cities in video games have been summarized in a table that fosters discussions and helps other scholars to explore the topic in further research. 3d representations of cities in video games are the result of a complex design problem driven by a vision that has as final aim the creation of a meaningful interactive experience. This research represents a further step of a larger and long-term project that intends to investigate aspects of video games that can bring innovative approaches, theories and reflections in architecture and related fields.

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A "BOUNDED ADOPTION" STRATEGY AND ITS PERFORMANCE EVALUATION OF VIRTUAL REALITY TECHNOLOGIES APPLIED IN ONLINE ARCHITECTURAL EDUCATION

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Abstract. Thousands of online virtual experiments are being developed by hundreds of National Virtual Experimental Teaching Demonstration Centers run by top universities in China. According to an analysis on the existing VR technologies accessible in market and the conditions of domestic universities, a "bounded adoption" strategy was raised by Tongji University, when it dealing with a daily teaching context. It puts the manpower and financial resources into the design of virtual experiments, so-called 'contents building', rather than equipment purchasing as before. After three new experiments built, an evaluation on their contributions to learning performance is conducted immediately, which tries to understand whether the strategy works and how to move on. As one of these experiments, learning a historic Chinese temple in an online way is compared with other four learning methods from traditional ways to hybrid ways. The result indicates that the VR technologies applied with the "bounded adoption" strategy have a positive coherence to high learning performance, especially in form oriented recognition task, which plays a key role in architectural education. Meanwhile, the current design of virtual task involving building process has to be improved.

Keywords. Architectural education; Online experiment; Virtual reality; Performance evaluation.

1. Background

With the vigorous development worldwide of "MOOC" and other online educational resources in various professional fields, the traditional architectural education also comes to "online" age. "Online virtual experiment" was proposed by scholars at the end of 20th century (Liang & Xia 2016) and it has been initially

developed as "web-based experiments" in many top universities, such as MIT and etc. (Yuan & Wu 2010). It can easily complete various experiments that cannot be carried out in the real world, because of long distance, operational risk, high cost, narrow space, or impossible to be carried out. Obviously, it is an important supplement of traditional experimental teaching in architectural education. In this case, the constructors in architectural background have to keep the balance between construction investment and the real improvement in learning performance carefully, which lies heavily on an understanding of VR technologies and an evaluation of the learning performance.

Since 2013, China Ministry of Education started a systematic establishment of online virtual experimental resources with the construction experiences in mechanical and electrical, aviation, national defense and other online virtual experiment pioneer specialty (Jiang & Jiang 2004), through building hundreds of National Virtual Experimental Teaching Centers. A batch of universities, such as Tongji University, South China University of Technology, Harbin Institute of Technology, Zhejiang University, China Central Academy of Fine Art, Beijing University of Civil Engineering and Architecture and etc. were appointed to setup their centers and to build online virtual experiments in architecture, which are expected to spread in China.

In this study, a "bounded adoption" strategy dealing with VR technology application and a corresponding evaluation on learning performance used by the center of Tongji University are introduced, which reflects the current development of those centers in China.

2. A "Bounded Adoption" Strategy in VR Applications

At present, with the commercialization, miniaturization of various hardware equipment, a large number of virtual technologies have been integrated into the educational vision of universities. Their implementation costs differ nearly a hundred thousand times (from Google cardboard glasses bow with less than 10 RMB to the immersive full-scale virtual environment with several million). Their functions involved shows unprecedented abundant from the audio-visual performance to interactive control, wearing and insertion, which undoubtedly led to difficulty in technical scheme selection for virtual experiment constructors outside VR industry. If twenty years ago, architectural universities tended to pursue "high-grade, precise and advanced" hardware. But now, the actual teaching requirements are placed with more attention. Some factors must be taken into account, such as the number of students who are simultaneously using the VR equipment, the size of the space occupied by equipment, as the number of supporting facilities and so on. Therefore, the online VR experiment construction team of Tongji University proposed a "Bounded Adoption" strategy when selecting and applying VR technologies.

First of all, a gene-like framework describing the capabilities of existing VR technologies in market is established (figure 1), in which 20 factors as genes are summarized under three big groups according to the "3I (Immersion, Interaction, Imagination)" features of VR technology (Portman et al. 2015). In general, op-

tions of any factor in the table from left to right, the cost of implementation and expectation on performance are both on the rise, except for the two orderly task options. With such a framework, even a constructor outside VR industry can easily understand the difference between any two technical schemes making a selection under limited budget.

Features	Factors	Options		
Immersion	View field	Narrow*	Wide	Panorama
	Acoustic model	Two-pole linear*	Field	Volume
	AV sync.	Inside view sync.*	Place sync.	Field sync.
	Tactile sense	No*	Feedback	Scaled feedbacks
	Muscle sense	No*	With strain	Scaled acceleration
	Vestibular sense	No*	Orientation	Scaled acceleration
Interaction	Delay	Obvious	Slight*	No delay
	Task	Passive task[1]	Active task	
			Sequential task	Parallel task[2, 3]*
	View orientation	Fixed	Dynamic*	
	Visual information	Fixed*	Switchable	
	Object's parameter	Fixed[1]	Adjustable[2, 3]	
	Object's position	Fixed*	Free	
	Object's orientation	Fixed*	Free	
	Object's path	Fixed*	Free	
	Object's relation	No[2, 3]	Establishable[2]	
	UI	Proxy Interface*	Body Interface	
Imagination	Abstract memory	No	Yes*	
	Imaginal memory	No	Yes*	
	Emotional memory	No*	Yes	
	Kinect memory	No[1, 3]	Yes[2]	

Figure 1. A gene-like framework depicting VR technologies in market.

Next, any proposed online VR experiment has to be depicted in the framework and the options fulfilling the requirements with the lowest hardware investment have be selected according to a real teaching context by an applicant leading an architectural course. A "Bounded Adoption" strategy in VR technology application means that the most of limited human and financial resources should be put into the design of experiment itself, especially the interaction process, which does not so heavily rely on hardware. For example, if the location of a component is a piece of key knowledge in a course, highlighting the component in a view of whole building contributes to students' understanding where it locates, no matter what immersive hardware they use. Only with such a strategy, online VR experiments can run on normal computers in a daily class. For example, the three running on-

line VR experiments in architecture of Tongji University have been planned with yellow options in figure1, which serve more than 200 students each.

Obviously, it is the applicant in architectural discipline who defines all the knowledge embed in an experiment and makes a proper design supported by VR technologies at an acceptable way for students. As soon as the definition and design are made, commercial software companies will make the development. In a case of affordable hardware upgrade in future, are these companies who upgrade the program to provide a better experience to students. However, it does not change the design of experiment itself, which is so called independence of experiment design for teachers.

Notes: yellow options are adopted by the three experiments in Tongji University. Superscript * : all of them adopt the option; superscript 1: experiment one adopts the option; superscript 2: experiment two adopts the option; superscript 3: experiment three adopts the experiment.

3. Development of Tongji's Online Virtual Experiments

Following the "Bounded Adoption" strategy, Virtual Experimental Teaching Center of Architecture, Urban planning & Landscape in Tongji University has been running three online VR experiments since early 2016. These experiments act as a start kick of an ambitious plan with more than 30 experiments serving the existing courses. An initial group of 19 interested teachers attended a VR technology demonstration show provided by local companies and three of them got the grants according to their clear experiment design with proper VR technologies selected.

The first experiment is called "Building components recognition and virtual construction for ancient Chinese temple" (figure 2). It is designed by Associate Prof. Tang Zhong and it is used in his course titled "Orders of ancient Chinese architecture", in which students carried out component recognition and virtual construction experiment in a case of Baoguo Temple in Ningbo. Every one of 407 building components and its historical information will be interactively learnt. Students can observe any construction node, dismantle and assembly it, to achieve a deeper study of traditional wood construction method, which is impossible to achieve in a real conservation building with more than 1000 years old.

The second experiment takes the name "Acoustic parameters of hall space" (figure 3). It is designed by Associate Prof. Mo Fangshuo and it is used in his course titled "Building Physics (Acoustics)", in which students have to complete an operation of reverberation time survey and experience the acoustic effects with different combinations of hall affective factors. It cannot be easily achieved in real experiments, because of the unavailability of the hall, expensive equipment, material replacement cost and time.

The third experiment is "Traffic control in residential block" (figure 4), designed by Associate Prof. Tang Yuqing and used in his course titled "Urban Road and Traffic". With on the traffic computing theory of residential area and a set of assumptions, students try to adjust the parameters of traffic system, such as road widths, percentages of different traffic types, peak and valley time periods, to optimize the land use of the area, which is totally impossible in real situation.

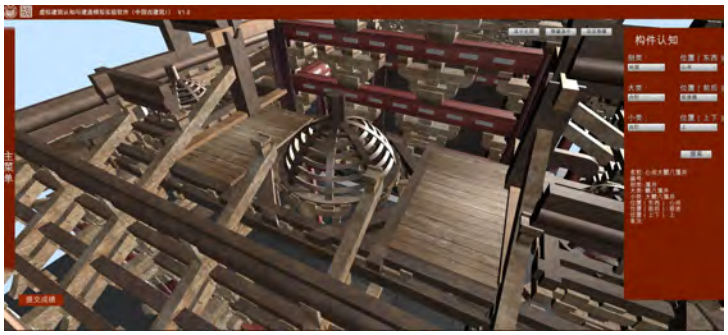


Figure 2. The recognition of a component.



Figure 3. The virtual stationing of hall reverberation time test.



Figure 4. The simulation with a set of traffic parameters.

4. Evaluation of Learning Performances

Although there are enough researches indicating that interaction improves learning performance upon objects involved (Gantt 2001), and it is almost affirmed that applying VR technologies in form-oriented learning plays a positive role (Huang 2005; Chen & Wang 2008; D'Souza et al. 2008), investors and constructors are still curious about the different performance among various VR technologies they select under the "Bounded Adoption" strategy. Thus, a systematic evaluation on the first experiment is conducted according to both objective and subjective methods (Gill et al. 2013; Ayer et al. 2016).

4.1. CHARACTERISTICS OF STUDENTS INVOLVED

There are 150 first year students (66 males and 84 females) in architecture involved in the evaluation. The average age is 19 and they haven't any knowledge about the ancient Chinese temple. Most males (61.9% boys and 17.2% girls) have experiences on 3D computer games and all of them have experiences on online shopping. Thus, they understand how to use the online virtual experiment naturally.

4.2. OBJECTIVE EVALUATION

The proposed objective evaluation tries to compare the students' knowledge gained by five different learning methods in the same learning time. In other words, the percentage of correct answers after learning indicates the learning performance of the corresponding learning method.

The subjects are randomly divided into five (A-E) groups each with 30 students. There are three steps in the evaluation:

Step I, every group learns the same knowledge (names of wood components and building steps of Baoguo Temple) through a specific method (table 1) in one hour: Group A is taught by a teacher (figure 5, left), who uses the traditional plans and sections in 2D drawings. Group B studies the books by themselves; Group C plays the online virtual experiment designed by the same teacher (figure 5, middle); Group D is taught by the teacher with virtual experiment demonstration (they do not operate by themselves); Group E listens to the teacher's brief explanation in 15 minutes and plays the online virtual experiment in 45 minutes.

Step II, every group answers the same 30 questions in 10 minutes just after the learning process (figure 5, right). The questions cover components recognition and building process understanding.

Step III, the learning performances, namely the percentages of correct answers of five groups are analyzed to indicate the contribution of VR technologies used in the current online virtual experiment developed with the "bounded adoption" strategy.

According to the performances indicated by average number of correct answers (figure 6), it finds out that the learning methods, involving interactive operation on online virtual experiment (Group C and E), get significantly higher scores of component recognition questions than others, which suggests the current development improves the learning performance indeed at least in this specific kind of knowledge. Obviously, it plays an important role in the discipline of architecture.

Table 1. The characteristics of the five 1-hour learning groups.

Group	Characteristics of the 1-hour learning		
	Virtual interaction (minutes)	Explanation on orders	3D visualization
A	0	Yes	No
B	0	No	No
C	60	No	Yes
D	0	Yes	Yes
E	45	Yes	Yes



Figure 5. The scenes of evaluation.

Furthermore, the performances on two kinds of knowledge, namely "component recognition" and "building process", are analyzed against three main factors (the duration of virtual interaction, whether there is teacher's oral explanation on orders among components, whether the temple is visualized in 3D). It indicates that longer duration of virtual interaction and 3D visualization obviously contribute to high performance if the knowledge of component recognition is concerned (figure 7). While it is not so evident in the case of building process (figure 8). Because VR technologies support the both contributing factors. It can explain why online virtual experiment has better performance than the others as found above.

In short, the learning methods with bounded VR technologies adopted have already shown advantages beyond the traditional methods at least facing with the knowledge of component recognition.

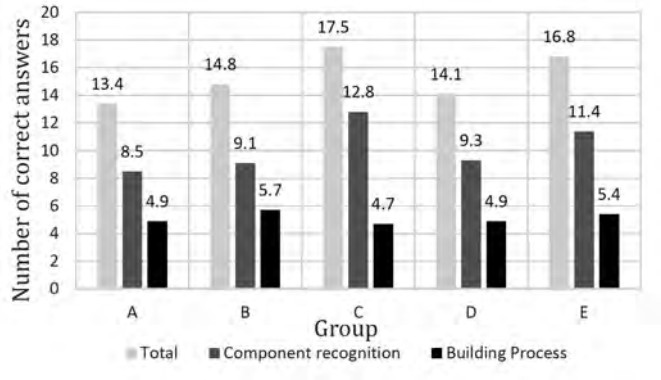


Figure 6. General performance of the five groups.

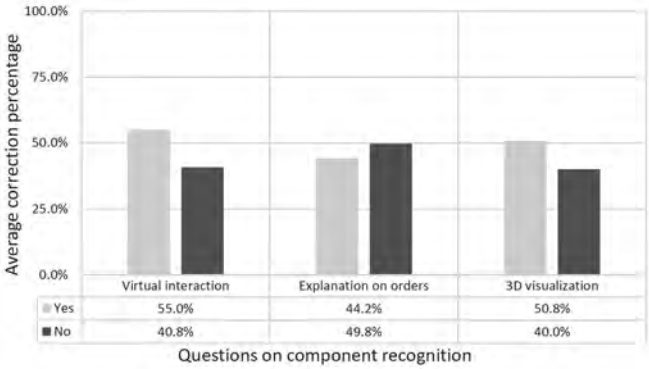


Figure 7. Influences of factors on component recognition learning.

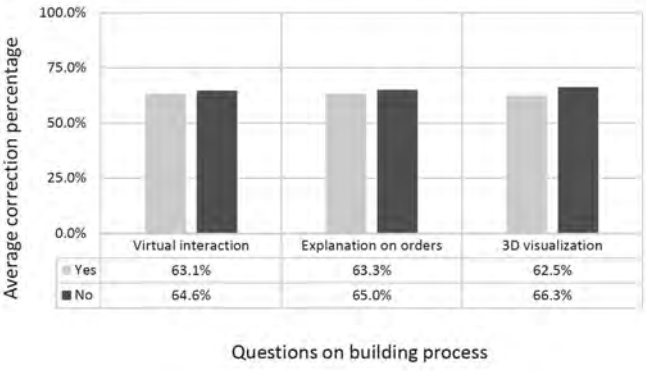


Figure 8. Influences of factors on building process learning.

4.3. SUBJECTIVE EVALUATION

Following the reply to the questions, the students in all groups submit feedbacks on their learning experiences, which cover the extent of pleasure from learning and the extent of interest inspired (figure 9). It is easy to find out that the three groups (C, D, E) using VR technologies are ranked top and Group B with support of books had the worst experiences as expected. In short, the bounded VR technologies adopted in the experiment have already enough improvement on subjective experiences for the students taking the traditional methods as competitors.

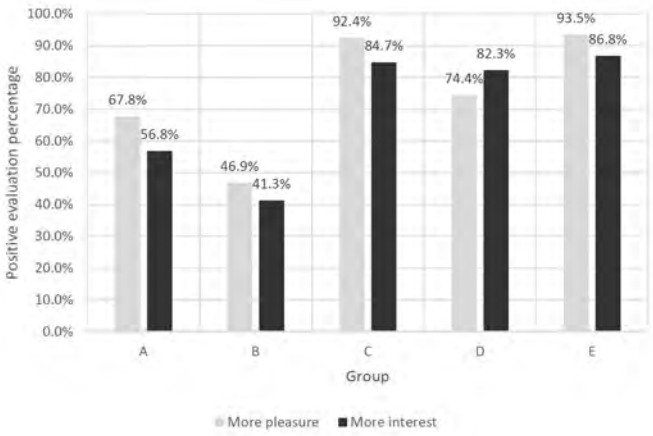


Figure 9. Feedbacks on learning experiences of the five groups.

5. Conclusions

Facing with the "online" age, the discipline of architectural is seeking an upgrade with the support from VR technologies. However, the balance between huge investment on cutting edge hardware and real teaching context with a large number of students is a conflict in front of universities in China. In this way, a "bounded adoption" strategy focusing on design of experiment rather than purchasing expensive hardware was raised by a team of Tongji University. Following this strategy, a gene-like framework is provided to help normal architectural teachers to understand the technologies and they can play central roles in the design of their own course-based online virtual experiment with cheapest technologies applied. Is the software company who helps them to turn their designs into final deliveries taking care for the various hardware. The result under the strategy is evaluated both in an objective and a subjective way, which indicates that the bounded VR technologies adopted in the experiment have an obvious contribution to the architectural education upgrade at least in the learning of component recognition knowledge.

Meanwhile, in this first round of construction, there is still many issues to improve, such as the design of interaction for the learning of building process knowledge. The current design with passive building task does not show any contribution to the upgrade. More complex active task (sequential task and parallel task) will be tested in the following construction.

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STREAMLINING THE MODELLING TO VIRTUAL REALITY PROCESS

Semi-Automating Mesh Quadrangulation and UV Unwrapping for Grasshopper.

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Abstract. Visualisation in architecture often involves a transition between different modelling programs. This is done in order to be able to manually prepare and repair three-dimensional models for visualisations such as renders and VR simulations. In this paper the development of a direct link between a three-dimensional modelling platform and a Virtual Reality (VR) Engine is investigated. This is researched through the generation and manipulation of clean quad mesh topology, UV mapping and UV texture map creation. Through a reiterative process, all possible solutions for improved quad mesh topology for doubly curved surfaces are explored. The resulting clean quad mesh improves the usability of the model and application of textures to accurately simulate a real material. In parallel, the development of a UV unwrapping and UV map creation process was investigated to enhance the texturing process inside the same architectural modelling platform. The overall system was developed as an advanced tool for semi-automating and streamlining the process between modelling and VR simulation. The paper concludes with the limitations of the process and points out to future research to improve speed and quality as well guides to where future testing and experiments should be further investigated and applied.

Keywords. Virtual Reality; Quadrangulation; UV unwrapping; Physics Simulation.

1. Introduction

This paper investigates the development of a parametric process to quadrangulate and UV unwrap doubly curved surfaces within the same parametric modelling platform. This is investigated in order to streamline the modelling to VR process. It describes the advantages and limitations of methods which do not feature mathematical algorithms or coding. The developed processes aim to increase the speed at which virtual architectural environments are developed.

1.1. PROBLEM STATEMENT

Visualisation in architecture often involves a transition between different modelling programs. This is done in order to be able to manually prepare and repair three-dimensional models for visualisations such as renders and VR simulations as shown in figure 1. This model preparation process can be time consuming as manual mesh recreation is "...slow and requires a lot of redundant user input" (Takayama 2013) which is why this project aims to investigate 'How to streamline the modelling to virtual reality process?'

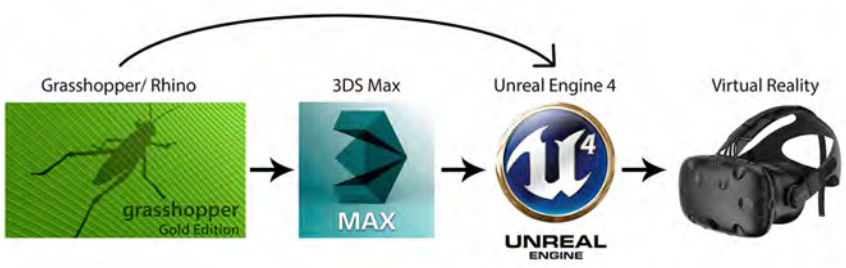


Figure 1. The current modelling to virtual reality process and what the project aims to streamline.

1.2. MOTIVATION

The process to prepare a model for visualisation can be slow as "...3D modeling is a time-consuming and skill intensive procedure" (Ji et al. 2010). If additional details must be added to a model for visualisation purposes such as subdividing a shape, adding edge loops to make a curve more prominent or UV unwrapping a model, this can be difficult if the model features irregular mesh topology. Such irregularities occur due to triangular faces which result in poor edge flow. This is important to resolve as "...designers often wish to explicitly control the edge flow and be able to prescribe precise positioning of edge loops" (Takayama 2013). Working with a mesh with good edge flow makes it much easier to work with as a "...quad mesh with good edge flow can represent a shape in a more natural way..." (Ji et al. 2010). This is one factor which would help to reduce the overall time to create a virtual environment due to the improved usability of the model. With the advancements in parametric software such as Grasshopper for Rhino 3D, and its gradual assimilation into the architectural office, a resolution to this issue using this software is investigated.

1.3. RESEARCH OBSERVATIONS

The current method to prepare and repair three-dimensional models for virtual reality simulations features manual processes, such as remeshing, UV unwrapping and texturing. It is these manual processes which this project aims to semi-automate through the use of a range of Grasshopper mesh analysis and manipulation plugins. These plugins can be used in such a way to help quadrangulate and UV unwrap a mesh. The investigation into this topic shows that there are currently many existing tools to quadrangulate and UV unwrap meshes, utilising complex coding and algorithmic approaches. However none of these tools have been integrated into Grasshopper. By developing an approach which simplifies the model preparation process and creating it within Grasshopper, will streamline this process as the model will be retained within a single parametric software.The use of VR is becoming more prominent in architecture offices which is because, graphically the "...ability to accurately represent environments has increased and the use of VR has broadened." (Portman et al. 2015) This improved visual fidelity and usability enhances the sensory experience of the simulation. The growing usage of VR shows the importance of quickly and efficiently developing virtual environments.In today's architectural society there has also been an "...increasing number of landmark buildings involving geometrically complex freeform skins and structures" (Pottmann et al. 2014). It is these shapes which are most susceptible to poor mesh topology due to the irregularities in their shape. By creating a model preparation process within a single program which resolves these issues for complex geometry, it will create a much more streamline modelling to VR process.

1.4. RESEARCH AIMS AND OBJECTIVES

The project aims to develop a semi-automatic process within Grasshopper which creates quad only meshes for open and closed doubly curved surfaces. The project also aims to develop a process within Grasshopper which UV unwraps a model and outputs a usable UV texture map for the model. This is investigated in order to remove the need to export a model to another modelling program, or at the very least, reduce the amount of time that the model is used within in an external modelling program. This will streamline the model preparation process for VR and make it more intuitive as all modelling tasks will be performed within one parametric program. The objectives of the project are to be completed using a simplified methodology when comparing to existing mathematical and algorithmic processes. Mathematical approaches for mesh quadrangulation require a thorough understanding of "...computational sciences, such as approximation theory, applied mathematics and finite elements modelling." (Bommes 2012). This project will aim to streamline the modelling to virtual reality process through the use of computational design methods and tools such as parametric modelling software.

2. Background Research

In the following we outline through a series of bullet points the background research:

- *Nurbs model visualisation preparation* - In order to transfer NURBS models into a virtual environment they must be converted to a polygon mesh as rendering is "...currently done via triangles." (Evans et al. 1996). This mesh triangulation process is automatic when rendering. Through the NURBS to mesh conversion process it can often result in poor mesh topology featuring triangle faces, poor UV spacing and inconsistencies in mesh faces. One of the issues of freeform architecture "... is the decomposition of a freeform shape into a quad-dominant mesh..." (Zadravec et al. 2010). The irregularities in mesh topology brought about by triangular faces, negatively impacts the usability of the model, in terms of texturing, model repairing and detailing. It is this issue which often leads to time consuming and difficult remeshing.
- *Comparing quad and triangle meshes* - When constructing a mesh, using quad faces is the preferred method when comparing to triangle or ngon faces. Quad faces are "an excellent match for texturing, as each patch can be trivially mapped to a rectangular texture." (Bommes 2012) This helps to remove distortion in the texture when the image is mapped to the model. When unwrapping models to create a UV texture, quads are also preferred as "...the loops become clearer" (Bommes 2012) which is evident in figure 2. Having a clear edge flow to a mesh is very helpful when selecting edge loops to separate the UV map.

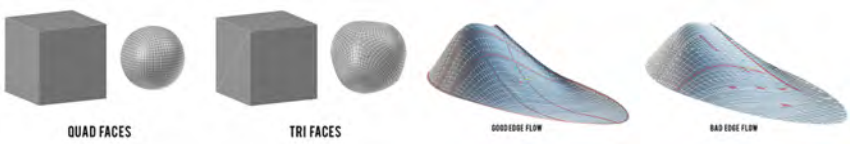


Figure 2. Image comparing the subdivision of a quad and tri faced cube (left) Image comparing good and bad examples of mesh edge flows (right).

- *Manuel remeshing process* - The manual re-meshing process involves placing points on the surface of the model, connecting them via edges and ultimately combining the edges into faces. Manually remeshing a model can be a time consuming task as "...it is often quite challenging even for professional artists to manually design a perfect quad mesh on the first try" (Takayama 2013). Performing this task multiple times can become repetitive and is an area of model preparation which has much potential to be semi-automated.
- *Existing Quadrangulation tools* - The development of quad only meshes has been a topic of discussion for a long period of time, resulting in the development of multiple approaches to resolve this problem. Many of these approaches have taken a mathematical and algorithmic approach which can be seen by the project Quad Meshing'. However, none of these examples have been directly integrated into the architectural modelling software, Grasshopper, nor have they used a non-mathematical approach.

- *Quad Meshing* - The reasons for the development of the 'Quad Meshing' project was due to "quadrilateral meshes [having] advantages for many applications..." (Bommes 2012) These reasons include quads being "more convenient and intuitive to manipulate then triangles.", because they are "...an excellent match for texturing..." and because they perform better when being subdivided which is a "modelling technique that [dominates] some industrial applications." (Bommes 2012) This project achieved these results by field guided methods developed by algorithms and coding which helped to establish the curvature of the mesh to generate the quad faced mesh.
- *Existing mesh texturing and unwrapping tools* - Mesh texturing tools are very limited within Grasshopper. 'Human' is the only Grasshopper plugin capable of applying textures to a model and UV unwrapping a model. This tool is very useful but is limited due to not outputting a usable texture map in which to place textures on. This is unlike poly modelling programs 3DS Max and Maya, which allow for the creation and manipulation of a UV texture map for a model. The issue with these programs are that they remove the model out of a parametric environment. Having a UV texture map is very useful for placing specific textures at specific parts of the mesh. (See also figure 2 for the above)

3. Research Methodology

The quadrangulation of doubly curved surfaces was divided into two groups; open and closed surfaces. This was due to these types of surfaces providing different geometry information. This was also implemented to simplify the methodology as there are many variables to consider when quadrangulating a mesh. A more universal approach was applied for the unwrapping and texturing of meshes. The created processes would be evaluated in areas such as speed and accuracy. Each area of evaluation would be ranked from one to three, one being poor results, two being average and three being excellent results.

- *Quadrangulation of meshes using physics simulation* - The proposed methodology for the project is a non-mathematical approach for the quadrangulation of meshes when comparing to existing code and mathematical quadrangulation processes. This methodology will feature computational methods through the use of Grasshopper and Kangaroo to simulate different forces to manipulate meshes into the desired shapes. This approach was chosen as the physics simulations allow the mesh to move in a natural way.
- *UV unwrapping using physics simulation and mesh analysis plugins* - Unwrapping and texturing the models will also be completed by using Grasshopper and the plugins Ivy, Human, Human UI and Kangaroo. These plugins were used as they allow for the deconstruction and manipulation of a mesh. Through a reiterative process of testing and evaluation, the final outcome will determine how well this non mathematical approach can complete the aims of the project.

4. Experiments

In the following we are listing the experiments undertaken in this research.

4.1. QUADRANGULATION OF OPEN DOUBLY CURVED SURFACES

The approach that was taken to quadrangulate open doubly curved surfaces used Kangaroo forces including gravity, collisions and anchor points. These forces combined would be used to wrap a flat quad mesh over a NURBS model. As seen in the figure 3, the NURBS model boundary outline is projected in a Z direction. This outline represents the boundary of the flattened mesh which will then be overlaid onto the NURBS model. The internal parts of the boundary are converted into a quad mesh through a grid system.

The flat mesh is then manipulated using Kangaroo forces, as seen in figure 4. The original surface is located directly above the flattened mesh to act as a collision in which the mesh will form around. Gravity is applied to pull the mesh downward to create an effect similar to a vacuum forming machine.

The simulation outputs a mesh with improved mesh topology without any complex algorithms which also reduced the number of faces in the mesh significantly, yet still accurately represented the mesh. In terms of VR usage, this is a positive aspect as less faces results in fewer calculations for rendering the geometry. Performing this quadrangulation process within Grasshopper means this process is entirely parametric allowing a user to easily adjust the amount of mesh faces there are. The results from this method are shown in table 1.



Figure 3. Developing the flat mesh for the Kangaroo physics simulation.



Figure 4. Performing the Kangaroo simulation to create a quadrangulated mesh.

Table 1. Open surface method results.

Method	Time to Perform	Mesh Quality	Mesh Accuracy	Applicability to shapes
Wrapping	3	2	3	1

4.2. QUADRANGULATION OF CLOSED DOUBLY CURVED SURFACES

The aim for the closed geometry element of the project was to successfully create a quad mesh of the Mesa Table by Zaha Hadid. This model was chosen due to the inability to obtain an architectural model featuring doubly curved surfaces. Although it is not a building element, it still features the complexities of a building form, including holes, branching elements and curved surfaces.

Inflation Method, is used as a method for quadrangulating closed doubly curved surfaces involves inflating a quad mesh from within the geometry. This internal mesh was created through the use of The T-Spline plugin by Autodesk for Rhino 3D. This plugin creates a single mesh from a series of lines and creates appropriate junctions in the mesh where necessary as shown in figure 5.

This method involves two Kangaroo simulations. The first simulation inflates the T-Spline mesh to the original shape by projecting the points of the internal mesh onto the surrounding geometry. The method was tested on the mesh as shown in figure 6.



Figure 5. Example of the T-Spline plugin creating the internal mesh from a series of lines and an example of an internal mesh for the Stanford Bunny.

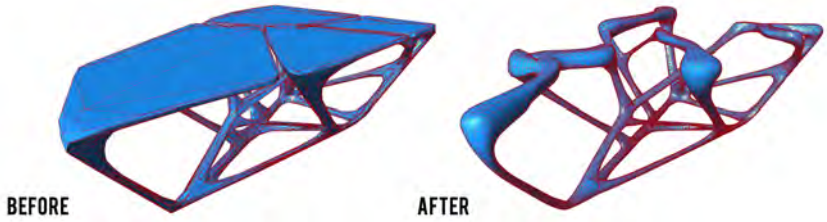


Figure 6. Quadrangulation of the Mesa Table by Zaha Hadid using the Inflation Method.

The points are projected according to the normal direction at that point of the internal mesh and become anchor points in which to pull the internal mesh to the bounding geometry. Laplachian smoothing is the second simulation and is performed to the mesh to average the distances between the vertices which creates a smoother mesh. The two simulations can be repeated any number of times in order to gain a more accurate representation of the bounding shape. This is due to the projected points not reaching all parts of the bounding geometry. This pro-

cess produced a mesh with excellent edge flow with no triangle faces.This method worked very well in some areas and very poorly in other areas. The biggest flaw with attempting to inflate a mesh was its inability to reach into all corners of the bounding geometry. The results from this method are shown in table 2.

Table 2. Inflation method results.

Method	Time to Perform	Mesh Quality	Mesh Accuracy	Applicability to shapes
Inflation	2	3	2	2

4.3. QUADRANGULATION OF CLOSED DOUBLY CURVED SURFACES

The approach that was taken to UV unwrap a mesh and generate a UV texture map for a mesh used a number of plugins to achieve this. The process shown in figure 7, involved unwrapping the mesh into a 2D representation, applying a texture to the flat mesh and then reverting the flat mesh back to its original shape.

Flattening a mesh was achieved with Ivy as it has the ability to unwrap meshes for fabrication purposes. Extracting a UV texture map would require Human UI due to its ability to take high resolution screenshots of models within its interface. This image would then be used to create a texture using Photoshop. Applying the texture to a mesh would be performed with Human by projecting the texture onto the flat mesh. Kangaroo would finally be used to revert the flat mesh with the applied texture back to its original shape by returning the mesh vertices back to their starting location. The results for this methods are shown in table 3.



Figure 7. UV Unwrapping and UV map generation of a sphere.

Table 3. UV Unwrapping and texturing method results.

Method	Time to Perform	Texture Quality
UV Unwrapping and Texturing	3	2

This process was applied to a sphere to test its performance in terms of the time to perform it and the quality of the texture when applied to the mesh. As seen in figure 7, the texture was successfully applied to the mesh however, when

reverting the mesh back to its original shape, some of the faces were placed in incorrect locations.

5. Limitations

We can identify two limitations, one in the quadrangulation method, the other in UV unwrapping and texturing method:

- *Quadrangulation methods* - The overall limitations with the investigated quadrangulation methods are that they do not work in all geometry types. The features that are good for the open surface method include, doubly curved surfaces that do not overlap themselves. The features that are good for the inflation method include tubular branching elements that have limited variations in thickness. Using Kangaroo simulations to perform mesh quadrangulation means the process isn't performed immediately, as the simulations can take time to perform depending on the number of points being manipulated. This process can therefore place restrictions on the level of detail in the mesh.
- *UV unwrapping and texturing method* - The limitations with UV unwrapping and texturing in Grasshopper through the tested approach, is that it is a slow method. The process also doesn't work on non-planar mesh faces as the Ivy plugin cannot unwrap these shapes. The mesh face placement is also an issue as it doesn't place some mesh faces in the correct location. The UV map itself is difficult to work with as the seams where the mesh splits are in irregular positions.

6. Evaluation, Significance and Future Research

The quadrangulation methods investigated in the project are a unique way to approach the issue, however in its current state they are not in a position to speed up the modelling to virtual reality process. This is due to the processes having limitations in terms of speed and accuracy. This project contains much significance, in particular for the architectural visualisation community as the methods and approaches discussed in the paper show an alternative way to prepare a model for a virtual reality simulation. Although this approach has limitations in terms of speed and quality, performing these tasks within Grasshopper is an achievement as this has limited precedent work. Semi-automating the quadrangulation process will help to avoid manual remeshing where "...a single mistake might require regeneration of the entire mesh." (Takayama 2013). Therefore visualisers will be able to focus more time on other areas of the visualisation process such as texturing or lighting.With the growing usage of parametric software in architecture due to its "...flexibility, over one which is static, and cannot be re-edited", (Maher 2011) allows for continual changes to be made to the model. The paper's quadrangulation method also has the ability to be applied to both meshes and NURBS models. This is beneficial as it's a more versatile quadrangulation method, as other quadrangulation tools either focus solely on either recreating a poor quality mesh using an existing mesh or generating a completely new mesh from a NURBS model. This project shows that UV unwrapping and UV map creation for meshes is possible within Grasshopper which is an area of limited precedent work. Although the dis-

cussed method for unwrapping and UV map development within Grasshopper has limitations, it shows potential for future research to be improved in terms of speed and quality. This project is significant for future reference, and is a guide as to where future testing and experiments should be further investigated and applied. The project proposes a method to quadrangulate, UV unwrap and texture a model within Grasshopper. The resulting meshes feature quad only faces and good edge flow. Textures were applied to meshes using a UV texture map produced within Grasshopper. An area for future work is to increase the level of applicability of the quadrangulation method to a wider range of shapes and to increase its ability to accurately replicate a given shape. This project shows much potential to be improved in the future and to help streamline the modelling to virtual reality process.

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GAMIFICATION FOR USER-ORIENTED HOUSING DESIGN

A Theoretical Review

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Abstract. Fluctuating economies and changing family demographics have increased the complexity in meeting the spatial needs for contemporary housing. Digital systems that allow flexibility are growing in demand but its rate of development is not catching up with the rapid changes. This paper explores how digital interventions can limit or help the process of collaborative design in high-density mass housing context. One key factor in user-oriented design system is participation. Many researchers have looked into system usability, design simplification and realistic visualisation to provide an immersive experience for users to engage the design. This paper argues how gamification acts as a form of decision support within a bigger framework model for a user-oriented digital design system. Using three levels of rules: constitutive rules, operational rules and implicit rules, the aim is for users to generate a housing design outcome not only for themselves but also collaboratively with other users through gamification.

Keywords. Gamification; user-oriented; digital intervention; decision support; mass housing.

1. Introduction

One of the most important tasks of the architect is the creation of space that reflects the desires and needs of the occupants. Despite the constant changes in the contemporary social demographics, the user groups in the housing market are experiencing an increase in its heterogeneity. These groups may have non-standardised spatial requirements that may not be best met by conventional designs. Unless the architect has the ability of mind-reading like Charles Xavier in the film *X-Men,* it is quite impossible for them to figure out everyone's desires collectively and

reasonably merge these into a single architectural endeavour. Yet, the demand is real, and there is a need for such a capability to gather the ideas and design collectively and efficiently. At present, architects have built mass housing based on experiences only through a few groups or individuals. The design process alone is already of high complexity with the need to account for building performances and buildability. With users involvement which is often complicated, non-linear, uncertain and dynamic, it is no wonder that most architects and other professions try to avoid exposure to it as a way to reduce the expenditure of further time cost and ultimately profit. This paper, conversely, describes the use of gamification as an instrument for the design of mass housing. The methodology enables architects to collect informative inputs conveniently, but also allows users to communicate their desires effectively and therefore facilitating collaboration between architects and users.

2. Gamification

The use of the term 'gamification' dates back to the beginning of the last century. In 1912 *Cracker Jack*, a snack brand, started to give toys as a gift in their products. Although gamification in this instance focuses on the domain of marketing to encourage more 'consumption', it is to describe the use of game design elements in non-game context (Deterding et al. 2011). Depending on familiarity, there are varying common assumptions towards gamification, but this research is meant to be 'collectively productive'. The following paragraph explains what gamification *is* and *is not*.

First of all, gamification is not turning everything into a game. The purpose of gamification is not to pull us out of reality but rather finding what is not boring in an activity that usually requires collaboration and engagement. This is neither to say that they are 'serious games' which are used as a training and learning environment such as in military and education. The focus of simulations in serious games is in testing the abilities of learners and on improving their skill sets in a virtual environment similar to real conditions. On the other hand, game theory is to mathematically analyse decision-making 'strategies' or individual 'choices' (Kelly 2003, 1), whereas gamification may be helpful to improve collaboration for 'a choice' and encourage involvement in 'a strategy' (Kapp 2012, 9). Also, points, badges and leaderboards (PBLs) are irrepressibly penetrating into every aspect of our daily lives in tandem with the growing use of social media. PBLs are one of the most common game elements. However, they are not sufficient with regards to what games and game design can provoke. The approach is to gamify a situation by thinking like a game designer, which is different than being a game designer. Instead of playing a game as a player, using a gamified system is still considered a user.

In the context of mass housing, the development towards gamification can adopt the three levels of game design rules: i) constitutive rules are the first, which are the abstract, core mathematical rules of a game. Putting it into the digital design context, this represents the essential algorithm within the system structure. They do not explicitly indicate how the users should enact these rules, but they

reflect the underlying framework of the system that informs the operational rules, the second rules. ii) The operational rules are the main 'rules of play' that users will have to follow when they are interacting with the design system. These rules directly influence the behaviour, input and output of the users and usually printed out as instruction or manual books. iii) Lastly, the third rules are the implicit ones, which are the 'unwritten rules'. They are the etiquette and behaviour of the users that usually go unstated. In game culture, these are well established as a form of 'sportsmanship'. How this can be achieved in the digital design context would be explored at the end of Section 4. Like game programs, digital tools of user-oriented design are multi-layered, complex objects. Specifying which aspects of a system belong to each type of rules are usually unclear. However, this three-part rule framework is applied to better understand the abstract formal system in achieving meaningful interaction through gamification.

3. The Participants

In every game, although the ideal players will be everybody, specific categories of players will still be the initial focus. Similarly, a gamified design structure will have its targeted audience. In housing supply/demand process, the major influential parties are architects and clients. (Friedman 2011). Zeisei (1981), separate the clients into two types; the *Paying Client* and the *Using Client*. The Paying Client refers to the builders or in the present known as the developers and contractors whose decision will determine if the housings get built. The Using Client refers to the users or occupants who will be living in the built housing which is also the primary intention of this research to adopt gamification at first. The Using Client is usually left out at the time of conceptualization, and they have very little say in the kind of housing that is built, yet home purchase involves the greatest single lifetime expenditure of their financial assets. This indicates that housing will not be just an economic dimension to the Using Client as compared to the Paying Client. The ability of the dwelling in satisfying needs and its characteristics such as location play a major role in determining the day-to-day quality of life the Using Client will have. Through the integration of gamification into housing design system, Using Client could directly be involved in the design process. The decision support that gamification provides could reduce the uncertainty and conflicts that usually exist in such participatory design process which would be further analysed in the next chapter.

Although the Using Client is the main consumer, the architect is still the primary role in the whole design process. They serve as a conduit to the technical aspect of building. There is currently an apparent gap between the Using Client and the architect (Friedman 2011). Most of the information exchanges and programmatic decisions are between the Paying Client and the architect directly. It is also usually the Paying Client who evaluates the design solutions and, if necessary, adjusts the requirements to fit their objectives. At this conceptualization stage, both the architect and Paying Client assume the role of the Paying Client and produce what they believe is the optimised living space. This exclusion of the Using Client may be derived from either objective reasons such as Paying Client

decides to initiate construction before selling the units or subjective reasons such as insufficient time and resources to incorporate the process (Friedman 2011). Here is where gamification could intervene to facilitate these problems.

4. The Model

Centuries of research and development towards social studies has always included housing as one of its key elements. Although supplying this need can be achieved through technologies such as prefabrication, it is still a challenge to provide the desired quality of living to every individual. This paper proposes a model that instead of architects producing one design and try to diverge towards each individual needs, the Using Client can take the baton of responsibility and design their own living space with the help of an open gamified design system. However, this does not mean that the architect has no involvement in the process. They have a bigger task to perform to accomplish - giving Using Client the ability to dream of alternatives. Architects are visionaries, they are able to realise and build dreams but this paper is seeking their capability to assist not one but a collective of such Using Client to build their dream collaboratively. This sounds almost impossible, and for this reason, part of the model for this gamified design system is inspired by John Wood's (2011) metadesign in achieving micro-utopia.

One major element in the metadesign as presented by Wood is a four-fold system visualised as a tetrahedral form (figure 1). The qualities of such a system help architects to think in a self-reflexive and dynamic way. Instead of a typical two-dimensional system, this unique form is three-dimensional, providing a manageable set of relations. The metadesign is being used in the here presented research context of a collaborative design system, providing a convenient method to get an overview of the complex problem. The components of the system are adjusted as follow:

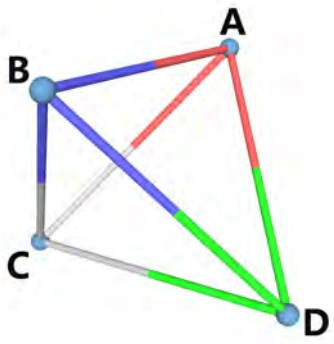


Figure 1. Tetrahedron depicting minimum grammar of relations (Wood 2007).

- A: Agent - the agent is the professional individual or anybody contextualised by nodes B to D. In this case A is the architect.
- B: Significant action or proposition in question - the gamified design system

that is proposed by this research.

- C: Recipient - Using Client who is the main target beneficiary.
- D: Full local and global context of A to C - the housing design task which this system is design for.

With the relations of the model properly laid out, the next step will be to zoom into details of how gamification serves the other components in the system. Strategising design parameters, information gathering and decision making are the key processes that have to be taken into consideration. This part of the model makes close reference of Avi Friedman's decision-making model for flexibility (2011). Figure 2 presents the adopted model with gamification being introduced to mediate housing design process as a decision support. This model breaks down the process into two scopes of exchange, the architect with the Paying Client setting the objectives and parameter with respect to the site context and regulation standards (A-D node) and architect with Using Client to determine the outcome of their desired living space (A-C node). Within the scopes of exchange, the model provides the connections of all twelve relations between the nodes including how gamification, being the key element in this research, could assist the architect in setting objectives (B-A node), provides for Using Client as a tool to generate alternative designs (B-C node) and bringing the generated design into the context for the architects to re-coordinate the overall design (B-D node).

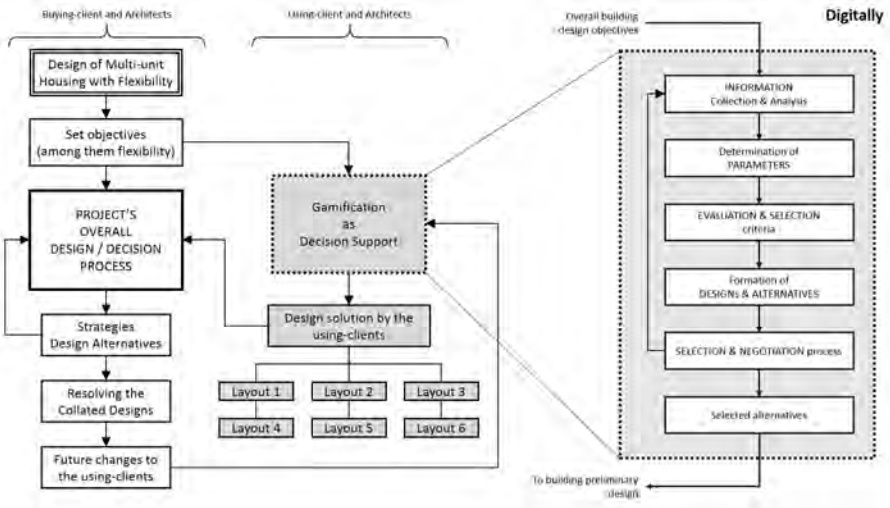


Figure 2. Friedman's (2011) adapted diagramme showing the digital intervention of gamification in the housing design process as decision support.

From this perspective, our research explores now how the three rules of gamification (Salen & Zimmerman 2003) will formulate these relations and inform how it supports such a housing design model. Various games provide a better picture in comparing and analysing the elements. To begin with, it is to examine the constitutive rules or the underlying structure that would inform the operational rules.

Looking at games such as *SimCity* and *Minecraft* which are two computer games frequently utilised in relation to architectural tasks (Sanchez 2015), although they are designed as open-world games where the players are required to design everything from 'tabula rasa', the players are confined and limited by rules and logics such as working in a grid environment and using building elements provided by the system. In comparison, the context of the system in this research is a high-density mass housing. There could be an open site context with surrounding buildings, streets and environment to explore but the main interaction will only be within the designated building. In other words, the design process is bounded within the confined housing design.

In another type of games, Role-Playing (computer) Games (RPG) such as *Mass Effect* and *Until Dawn*, which follow a particular storyline, require players to make decisions that change the course of the story resulting in individual and unique endings for each player. The players simply need to make choices. They are not required to keep score or follow complex rules. The story, however, will be adjusted according to the choices made by the players resulting in different story endings. Such a decision-making method could also assist greatly in a user-oriented housing design. The architects could prepare a framework mapping out every decision towards the number of outcomes they would want (figure 3).

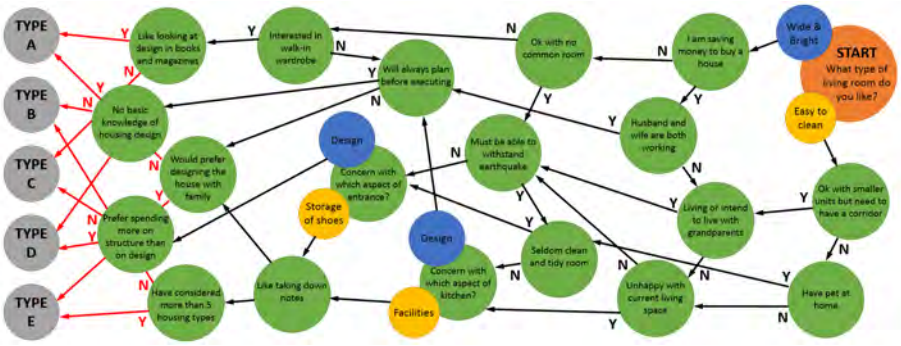


Figure 3. An example mapping of decision-making framework (Taniguchi 2012).

The role of the architect and the Using Client also affect the constitutive rules greatly. The Using Client is simply a single individual, a couple or a family settling to live in an apartment. Their objective is simply to design a desirable outcome. Therefore, they have more limitations compared to the architect who is the creator of the whole context. Another example to better illustrate this point is *Super Mario Maker*, a game which does not only allow players to play but also design and build their own game stage. This breaks the traditional form of playing where players will only try to beat the levels designed by the game designer. In the maker-game, the player is opened to more constitutive rules allowing them to create more random stages for other players to play. Yet, the player is still restricted to a certain structure compared to the game designer. After close examination, it can be anticipated that the relationship between the game designers and players is very similar to that of architects and Using Client. This can be further observed within the

influence of the different gamification rules.

In the realm of operational rules or the rules that most directly influence the Using Client, the gamified design system is both wide open and relatively closed off. The Using Client is given more freedom and availability in the choices such as layout arrangement, building materials or dimension. They are provided with an incredibly detailed view of the site context and building structure laid out in front of them. They can move about freely to explore the site, build their living space in whatever manner they prefer. The process is simplified to be manipulated easily; they only need to generate the spatial layout map through the digital system and the plans will be generated automatically (figure 4) for further adjustments. They can also communicate and design together with other users. On the other hand, however, the design is still restricted to the grid designed by the architect. The 'freedom' of choices is also restricted to the range of choices decided by the architect. The purpose of such constraint is because more choices do not mean more freedom or welfare (Schwartz 2004). This is also to ensure a certain order within the design system so the outcome will not be chaotic. That is the reason for which this paper stated that the architect has a bigger responsibility with such a system; they have to assess the process and outcome assisting the Using Client in making the suitable choices. If the Using Client is still not satisfied and provided a sound argument and alternative design, the architect will have to make the final decision which would affect the process and outcome. Although this may sound tedious, the increase in the anticipation of Using Client would also greatly build up their sense of ownership which bring about greater sustainability of the building (Israel 2012). In any case, the operational rules are the most accessible and understandable for the Using Client to follow during the whole process.

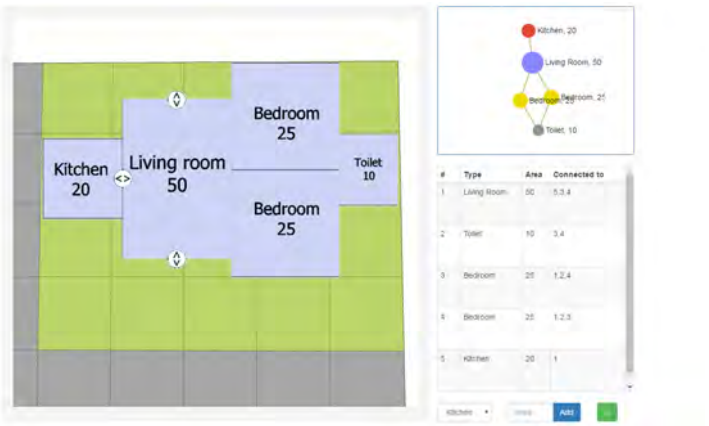


Figure 4. A tentative operation process of the using client in designing their living space.

There is one main feature in games that is not adopted altogether in this gamified system - the objective. In games, that serves as a guide to players which keeps them on track with the game, be it the main quest to advance through the story or a side quest to enhance the attributes of the game character. This feature sits in-

between the constitutive and operational rules. In the proposed gamified design system, there is neither storyline nor character. Such a feature, therefore, serves no purpose, yet an objective is necessary and in fact, exist in every Using Client. Additionally, this 'objective' is very different from every Using Client. Thus, instead of the architect setting a set of objectives for every Using Client to follow, the gamified system will tailor a unique set of objectives for every Using Client based on their needs and preferences. The user will have to fill up a set of questionnaires before accessing the system. Such a feature is part of the constitutive rules of the gamified system, but they also serve as operational rules as the users will then have to comply and try to achieve their own objectives.

Another key feature that is adapted from gameplay is the 'massive multiplayer online role-playing games' (MMORPG). This is the part where this research and proposed design system greatly differs from the rest of the existing systems. Most of the available systems such as *Wikihouse*, *iPrefab*, *BarCode Housing*, are designed for users to design their own houses. There is a lack of communication between users and designing as a community. One main reason is that including a group of users will exponentially increase the already complex housing design. However, online communities have proven, through MMO popular culture, their potential in providing powerful problem-solving capacities through collective intelligence (Segard 2013). Games such as *Clash of Clans* and *Mobile Strike* are famous mobile application games that call for strategies among players. Players need to understand the capabilities of each teammate and communicate well to execute the best performance against common enemies. New friends and communities were formed from these games; internet forums were created to allow discussion of battle strategies, etc. The key point here is that through a process that requires strategies, people tend to communicate with each other to pick up the best strategy that suits them and through this communication, builds up communities and relationships that push them towards solving problems together. There is clearly great potential to integrate this capability into an online digital housing design system in hope to bring about a collective design that an architect would not be able to generate alone. Yet, even with gamification, the whole process is not implemented easily. There is a crucial precondition, which could be controversial; every participating Using Client can not be anonymous as compared to MMORPG.

This leads to the next implicit rules which are also the most important rule in the gamified design system. The design process depends on the participation of every Using Client, and there is no particular control over such action. Therefore, the success of this model falls heavily towards these unwritten rules. There are three key points for an accurate user-oriented collaboration to be initiated; communication, transparency, and understanding (Lo et al. 2015). Every aspect of the gamification is to bring about these points among Using Clients. Context variables such as socio-economic background, rate of mobility, life stage and living quality preferences are some necessary information to ensure this gamified design process produce the relevant result. The level of information comes in two levels; Level I are general information that influences design decisions and Level II are analysed information that responds to the needs of the Using Client. In additional

to providing truthful personal information, timely feedback is also necessary to determine criteria for their selections. These will reduce the uncertainties of such participatory process. The aim of gamification is to anticipate the users into the process and provide the information with ease and confidence.

5. The Next Stage

We carried out pilot studies, the technical aspects and functions is explained in Lo et al. (2015). This paper provides a more detailed explanation of the purpose of gamification. As gathered through the study, our gamified housing design system provides a versatile structure to enhance the participatory process between the architects and the Using Client. On the one hand, the Using Client can design their living space with ease while the architects, on the other hand, can obtain real information that assist them to provide better design solutions. This is a win-win situation as suggested by Wood's tetrahedron model (figure 1). There are, however, still many potentials in further enhancing this gamified experience. One current disadvantage is that this participatory process still involves a keyboard and a screen. Some physical models could be added to enhance real interaction with the model data feeding into the system directly but this would mean an increase of necessary resources. With the recent growth in interest towards Virtual Environments (VE) and Augmented Reality, from multi-touch tabletop (Chen & Schnabel 2011), to VE CAVES (Frost & Warren 2000), the next step to provide a more immersive and sustainable experience could be towards this as well (figure 5).



Figure 5. A participant manipulation a virtual space using VE.

6. Conclusion

In conclusion this paper argues that a more powerful tool might not be the only way to resolve challenges. Other methods, such as gamification, can provide an alternative, more engaging ways of operation of designing housing which in turn, enhance the outcome as being more user-orientated. Since digital intervention is inevitable and necessary in the complexity of housing design, gamification could provide a compelling bridge between the architects and the Using Client. This paper has structured the models at different levels of the engagement and integrated in such a way that the resulting model system is conclusive before the gamification rules can come into play. This is to build up the foundation of the design purpose

which is necessary to demonstrate that there is a need for gamification to facilitate the process. Subsequently, the aim of gamification as a methodology is for users to understand one another through certain transparency in the information they provide and they can understand. With seamless communication on top of that, the research presents a particular approach to forming a desirable pre-construction housing community.

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DIGITAL CONSTRUCTION

Demonstration of Interactive Assembly Using Smart Discrete Papers with RFID and AR codes

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Abstract. This paper proposes and examines a new way of cooperation between human workers and machine intelligence in architectural scale construction. For the transfer of construction information between the physical and digital world, mature technologies such as Radio Frequency IDentifier (RFID), and emerging technologies like Augmented Reality (AR) are used in parallel to supplement each other. Dynamic data flow is implemented to synchronize digital and physical models by following the ID signatures of individual building parts. The contributions of this paper includes the demonstration of current technological limitations, and the proposal of a hybrid system between human and computer, which is tested in order to explore the possibilities of digitally enhanced construction methods.

Keywords. Digital Construction; Augmented Reality; Human-Machine interaction.

1. Concept of Digital Constuction

'Digital Construction (DC)' is a construction method that consists of both conventional construction and applied ICT. The aim of this research is to materialize digital data into physical objects in a context of architectural construction. Different from digital design (DD), DC emphasizes on construction process. Different from digital fabrication (DF), DC emphasizes on architectural matters rather than industrial products. This differentiation is necessary because architectural construction relies on a wide range of technologies to assemble many discrete and diversified

parts. This assembling process is mostly executed outdoor on-site. In addition, construction methods and processes are customized in individual situations, taking accounts of factors such as site conditions, form, and program of the buildings. Furthermore, construction processes involve various tasks with a different level of detail, all of them require accuracy in execution. Thus, DC covers a much more comprehensive scope in architecture or civil engineering structure than DF.

1.1. BACKGROUND

Construction field has not been fully developed in terms of ICT / IoT usage in the current situation (Manyika 2015). In emerging markets, the construction industry has been expanding (IHS Global Construction Outlook 2015). Thus it requires accurate work of semi-skilled workers and effective logistics in construction using ICT. On the other hand, in developed countries, the reducing number of workable labor and the diminishing techniques in construction field are problematic issues.

Recently, mass-customization technologies for non-standardized parts have been developed (Poorang 2013). ICT in a design field, such as building information modeling (BIM), facilitates the design of complex form of architectures. DC connects these to construction can ensure construction accuracy for 'non-box' types of architecture, as well as reduce costs. These attempts will contribute to the liberation of architectural forms and make it possible to pursue the value and performance of architecture more than ever. Thus, DC will make a huge impact not only on architectural design but also on related economic, social aspects (figure 1). In the past, there were several attempts in architectural design and construction field respectively (IAARC 2011).

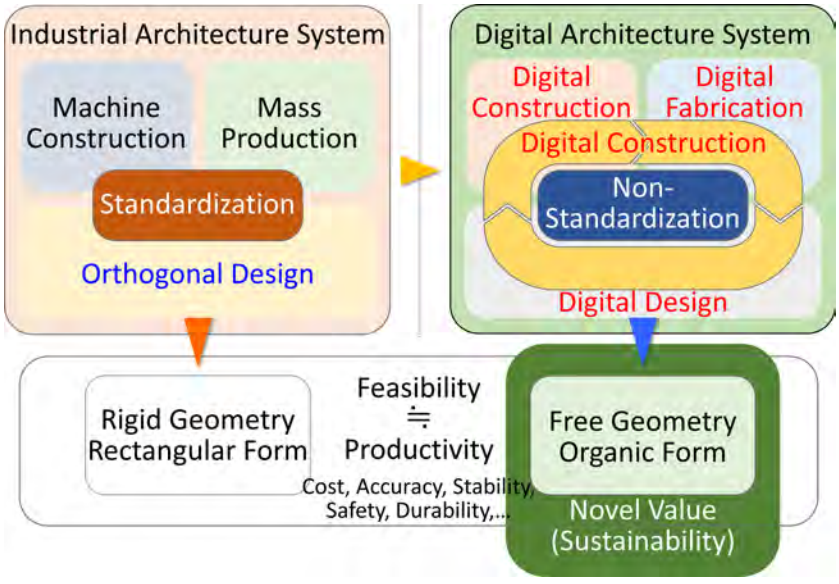


Figure 1. Diagram of industrial architecture system and information architecture system.

1.2. STATE OF ART

There are a number of technologies that can be applied in DC. In order to implement digital data into the real, positioning function would be a key technology. There are several machines that can be applied to assemble / fabricate parts. These technologies include the following: robotic arm, three axis computerized numerical controlled machine, unmanned aerial vehicle (figure 2).

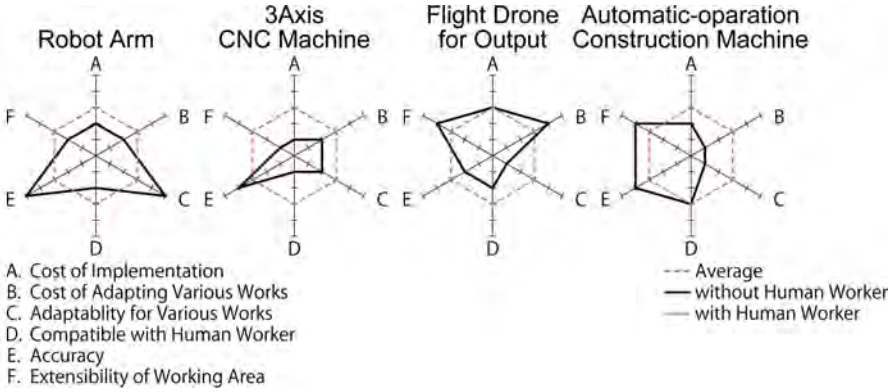


Figure 2. The methods that outputting digital data into physical coordinates.

Also there are techniques that can be applied for converting information from physical environment to digital data. By acquiring information such as three dimensional shape, type of parts and construction condition. These technologies include the following; 3D scanning with laser rangefinder or photogrammetry, position tracking (Wi-Fi / Bluetooth), target marker by image processing, RFID, UAV (figure 3).

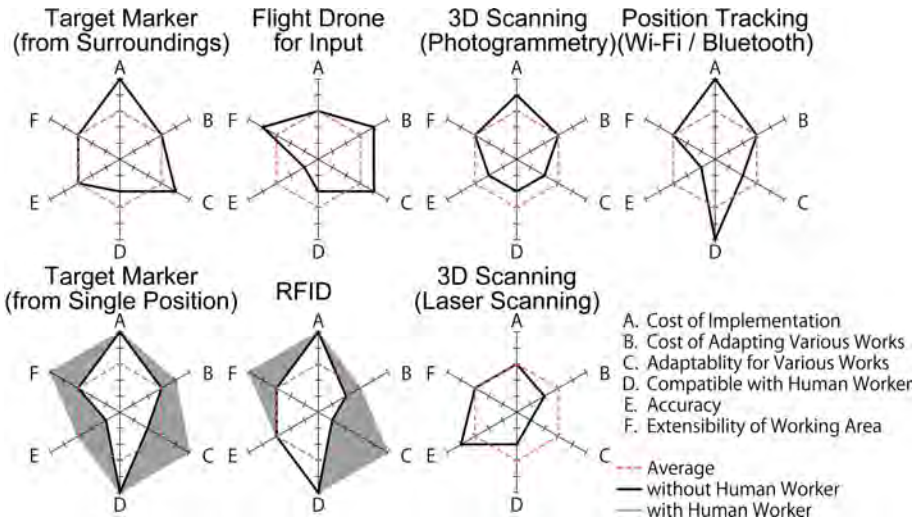


Figure 3. The methods that inputting physical information into digital data.

1.3. PROBLEM STATEMENT

The ultimate purpose of DC is to materialize a digital data into a physical object in a construction. However, there are few technologies that can replace a human construction work completely. In the construction process, worker/machine has to adapt to various sort, scale, and accuracy of operations. Also, a high environmental recognition ability is required. In addition, humans need to intervene in construction. In each process of construction, data conversion is necessary for each purpose. Yet, the certainty of data conversion is not guaranteed, and data conversion is often not reversible. Above that, data cannot be circulated for design communication. Finally, despite that information is necessary to continue to update as the physical situation changes, there is no platform that can integrate all information for construction.

1.4. ARGUMENT / CATEGORIZATION OF THE DC

With above research, different types of DC are given through several degrees of automation. Category-1: defined as the construction methods that are is fully automated. The digital data is directly inputted to a machine, the physical condition of materialized parts is get by the system itself and system will adjust its virtual model without a human. Category-2: defined as a construction method that is partially automated. Operated by human and machine loaded with data . Basically, machines are used only for their powerful and relentless aspect, such as repeating, counting, identifying. A human worker helps for circumstances recognition. Category-3: defined as the construction methods that enhancing a human ability by machine/computer power. It compensate shortcoming of the human operator and the whole system exerts performance more than a single system (figure 4).

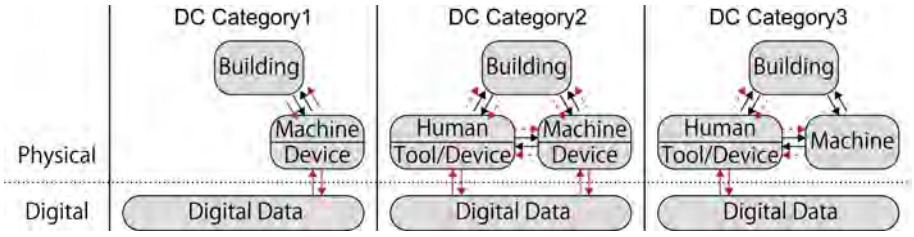


Figure 4. Three DC categories.

2. 'Smart Block' Project as Experimental Model Study

Following the prescribed DC concept, 'Smart Block Project' is proposed as a case study in here. Firstly, the precedents by the same research group are introduced. Then, the proposal concept is led. Secondly, the comparison of technical methods makes specification. Thirdly, the experimental model and head mount display (HMD) guiding system are shown, then have the review and argument.

2.1. BACKGROUND, ART

Digital Woods (Ikeda-lab 2010) is a concept building and its metabolism system consists of a large number of wooden blocks that can be changed by user's demand. Structures, stairs, finishes, furniture, etc. are built with the same blocks. Thus, the building space can be re-configurable by rearranging the parts. Authors propose to embed an electrical identifier into the parts to construct effectively. For the operation in construction, the user/constructor refer this information in order to deal with the proper assembling order and places. This system records all the construction process. In this point, the author could not implement as real technology (figure 5).

Porous Torus (Ikeda-lab 2010) is a temporal pavilion by using parametric design (one of the DD) and laser cutting (one of the DF). Yet this can be said as an experiment to assemble non-standardized parts by un-digitized construction (without DC). The following points are reviewed: firstly, Parts identifications without any guide extremely laborious work, since mistakes frequently happen. Secondly, it is difficult to confirm whether the parts are assembled in the proper position at the time of construction. These high-lightened the importance of digitizing construction (figure 5).



Digital Woods (Ikeda-lab, 2010) Porous Torus (Ikeda-lab, 2010)

Figure 5. Precedent projects, Digital Woods and Porous Torus.

2.2. AIM, HYPOTHETICAL PROPOSAL

The aim of this section is to demonstrate the working system which enhancing human and machine (category-3), as leading proposal of DC (figure 6). Reviewing arts essential functions are given as following: 1) Position tracking, by using AR target marker 2) Identifying similar parts by RFID, 3) Work guidance for human by presenting information, 4) Automated synchronizing system between digital model and physical construction state.

There are two potential methods to synchronize between digital and physical model. One is scanning, to get the most recent status of the physical object. But this method need to detect location (three dimensional coordination) or after-process to dismantle mass to parts. The advantage of detect location is an ability to detect parts position and individual identification simultaneously, yet it is difficult. Other is assuming the state of the physical building by logging the sequential process. 'Logging' method does not need a location detection, so that just for chasing parts AR marker detection and RFID are used in here.

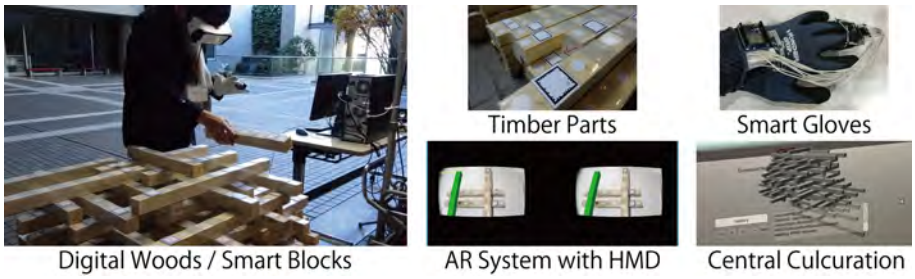


Figure 6. Smart Block project.

2.3. METHOD / TECHNOLOGIES

Here, the used technologies and products are explained its selection reasons. A practical knowledge for implementation is revealed too (figure 7).

- Parts design for identified timbers: AR markers and RFID tags are attached on timber patrs, have joint at 45mm pitch. Both are inexpensive, for instance former is less than 1 Japanese-yen, latter is around 10 Japanese-yen. Other advantage is these are able to affix on parts tier post-production.
- Physical computing parts for smart gloves: the function of smart globes is recognizing individual IDs, that is on each joint of each timber parts. This glove sends a joint ID to the main computer by touching. Parts details are described following. 'Espr8266' is used for micro-controller embedded Wi-Fi module that is an Arduino compatible and runs with 3.3V mobile battery. Considering actual construction on the site, the smart globe needs to be wearable, wireless and compact. 'NFCTag Circus NTAG213 WPP60' is used for RFID tags. It needs to be small, thin not to physically disturb the timber parts. The cheaper tag is the better because of a large quantities tags required. The readable area should be limited to 50mm (size of joint). 'MFRC-522' is used for RFID is antenna device for reader and writer 13.54MHz band passive RFID tag. This is compatible with Arduino too.
- Application development for device to present information: AR system with HMD was adopted for information visualization device. For Simultaneous Localization and Mapping (SLAM) technology using AR markers, the method was adopted that calculating the relative position of parts from AR markers affixed to individual parts. this method takes a cost to register and manage AR markers according to the number of timber, but the precision of the position matching is high compared to the method that setting the AR marker in the peripheral space and calculate the absolute coordinates of the space. Ultimately, we developed an automatic marker generation system. Concretely, 'Gear VR+Galaxy S6 edge' is used for this HMD. GearVR is cheaper than other devices and has functions about a width of the display, high display resolution, and high refresh rate. It works wireless and does not need external device is required for SLAM. 'Unity+Vuforia' (for Android OS) is used for DE of AR system. Unity (Unity technology Inc 2009) and Vuforia (Qualcomm 2011-2016) is chosen for the following reason. This application does not depend on marker type, have high ability to recognize markers and SLAM supplement

function at marker missing time. Also, there were many documents to refer.

- Software implementation for central calculation: the central calculation receives information from the glove device, calculate a ghost timbers position, generate and send an AR view, calculate a structural balance, receive operation from HMD device. 'Unity+C-Sharp' is used for central calculation; DE for Unity is adopted C-Sharp, other DE (javascript, Boo) have some problem.

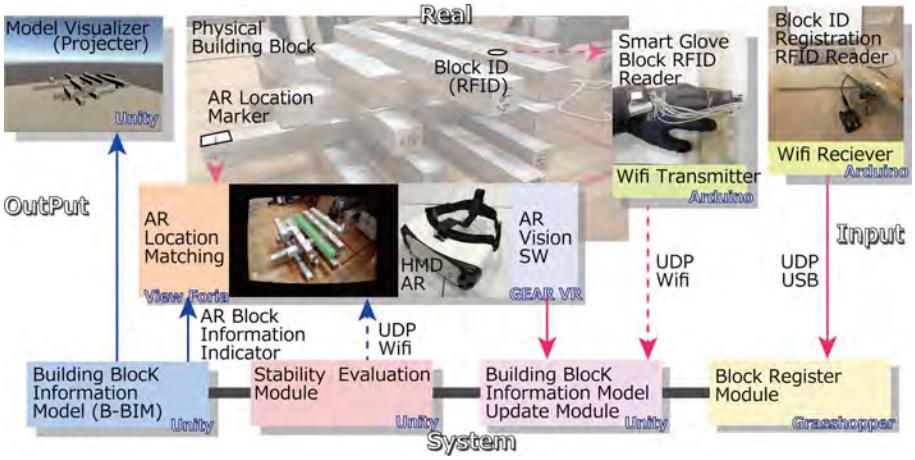


Figure 7. System diagram.

2.4. EVALUATE THIS SYSTEM

AR system with HMD was adopted as information visualization because that is superior to other devices on construction sites in the following points: 1) the amount of information that can be displayed is relatively high, 2) easiness of cross-reference between information and real, 3) flexibility of place to present information, 4) degree of an obstacle to construction work (figure 8).

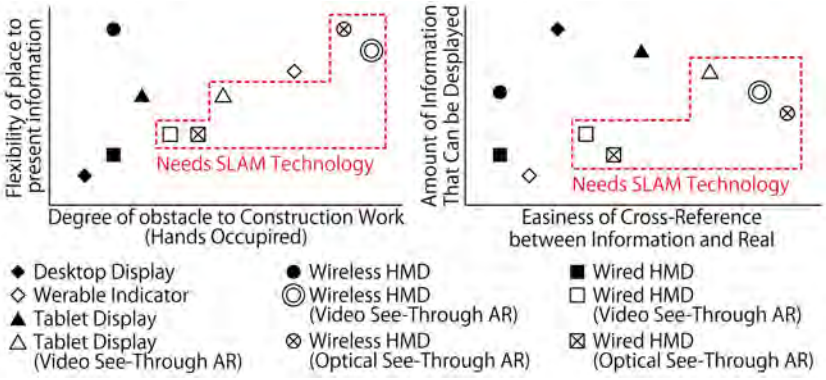


Figure 8. Comparison various system for information representation.

13.56MHz passive RFID was superior in the reliability of reading, strength against a physical obstacle, smallness, thinness, and permanence (figure 9). This has a short communication range, but in this system, this performance worked rather advantageously as a high reading position accuracy. However, poor affinity with metal materials, high cost, large read antenna is a factor in reconsidering.

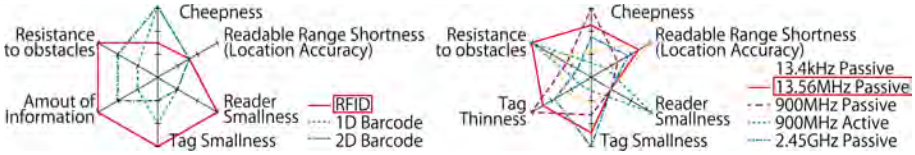


Figure 9. Comparison various system for identification.

The advantage of this system is following. Firstly, it is a 'light' technology (cheap and easy to attach). Affixing is the only operation rather than replacing the existing systems and products. Secondly, the system can try simulation low-costly in data space than the real space. Only when feedback are needed, system can output the results to a real space. Finally, the response time for the better decision may able to reduce by using this system. There are a both cases: the case instant intuitive response is needed, but on the other case deep consideration or calculation takes a long time. If the system is smart enough, it would choose appropriate algorithms inside.

Shortcomings of proposed system are following. Firstly, Inaccuracy of target AR marker are revealed. It has errors 10mm-50mm between displayed object and real object, because of camera, and its calibration. In order to solve those issues, physical design make constrain for way of piling. Concretely timber has step joints at 45mm pitch, so that those can not place wrong position. However it does not have generality for other design. Secondly, trouble in implementing a device to present information are following. To pursue real-time HMD display with video see-trough type, Galaxy S6 edge was not enough in computational power. Over heart of HMD frequently occurred due to high load calculation. As well as some functions of Unity are insufficient to deal with thread processing. Thirdly, registration parts is another trouble factor. Seventeen RFIDs and four AR markers for each parts require to be registered. This process required a huge amount of labor and caused many registration mistakes, that leads to a fatal system error in the subsequent test operation. The most frequent trouble in the test process were caused by tag mismatch due to a mistake in registration. The registration error is not only troublesome but also affects the synchronization of the model and the data. In this system, debugging by cross-referencing data and actual things like this registration error is indispensable. Also detecting those error without interface for human is difficult. Fourthly, misunderstanding of the presented information and instructions. In order to solve these problems, improvement of the GUI for operation are needed. True superior user interface does not need instruction. Finally, tangible feeling trough HMD was uncomfortable in many way. The experience was like a phantom limb effect with distance-lag, as well as time-lag makes this feeling, because every visual information comes from the camera. Technically speaking,

parallax, response speed of visualization, these sort of problems has to be solved but that may have exist UI research field. Since this proposed system help workers to assemble physical parts, so that this intuitive feeling would be crucial on site.

3. Conclusions

DC was categorized by examining existing technologies. From this categorization, it is concluded that a hybrid system between machine and human is the most practical proposal. Precedent research shows the required and essential three functions for DC. The hypothes are that the DC that satisfies these three functions can be realized by hybridizing AR and RFID technologies. Implementation of this system was successful. Through troubles in the development and testing phase, this system's limited precision are revealed. Eliminating human error s in parts manufacturing and system registration phase is quite hard to avoid completely, but may cause fatal situation. The design of tangible feelings and GUI for operation/ error detection are important.

Architectural contribution of this system is that it makes possible new design methods (a relationship between planning and construction in design). There are several possible methods between these four poles, since this proposal would support a method located in the middle (figure 10). Although there is no drawing prepared in advance, construction proceeds according to a blurred image in the architects (or layperson) mind. However, it based on the support of calculations by machines, it is also possible to make improvised changes by humans. 1) Completion is decided in advance, construction follows a static blueprint. 2) Construction is controlled by the algorithm, completion is decided sequentially. 3) A design method that evidence based on the computational study. 4) Improvised design method including changes by accident, impulses, whims.

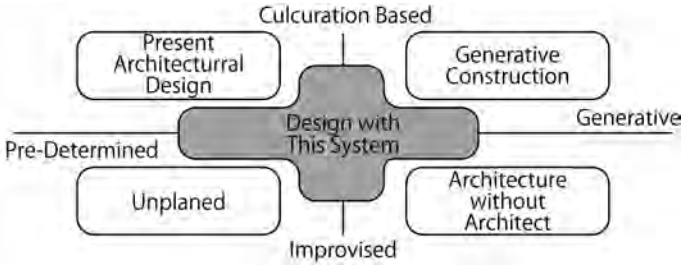


Figure 10. Map of design methods.

For future prospects, three diffrent systems revealed by considering the superiority and the inferiority of both in human and machine.

1. This system would notify human what is the right answers. For instance, this system indicates where to place parts safely in the structural point of view. Referring from the analogy of 'jigsaw puzzles', the answer is indicated by system, so the only task of the human is to put the right piece into the right place.
2. This system also guide human but adapting sudden change of conditions, even there are no right answers. This can be a speculative application in higher levels.

For example in construction, even in the midway of building, change of condition can be happen due to accidents, change of minds, or unexpected change of circumstances. This system performs alike 'car navigation system', even the user makes an mistake, resistance to suggestion, a system can adapt to new conditions and guide user to a destination, in anyway.

3. The system encourage human to achieve a certain objective by utilizing game, often called gamification. If the user finds pleasure of interacting with the system, this system can potentially become a new type of 'collaboration game' and develop its own ecology. At that stage, the GUI is the communication channel between the human and the system, and inevitably those virtual buttons are placed to the AR space.

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INTEGRATING BIM, CFD AND AR FOR THERMAL ASSESSMENT OF INDOOR GREENERY

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Abstract. The renovation projects to improve the thermal environment are gaining importance because of energy saving effects and occupants' health considerations. However, the indoor thermal design is not usually performed in a very efficient manner by owners and designers because the architectural design data including the indoor thermal design is not centrally managed among all professional designers. Additionally, the visualizations of the CFD simulation results are difficult for the stakeholders to understand. On the other hand, greenery has been introduced to buildings as a method for adjusting the thermal condition. The research goal presented in this paper is to investigate a cooperative architectural design process for the thermal environment by developing a system in which BIM, CFD, and AR are integrated to provide interactive visualizations. Case studies are performed to verify the developed system and to assess the thermal effects of multiple indoor greenery design options.

Keywords. Interdisciplinary Computational Design; Indoor Thermal Environment; Computational Fluid Dynamics (CFD); Augmented Reality (AR); Indoor Greenery.

1. Introduction

The renovation projects in the field of the architecture are gaining im-portance as they can replace costly construction projects of new build-ings. Recently, renovation projects to improve the thermal environment are more frequent due to energy saving (Marszal et al. 2011) and occu-pants' health considerations (Laschewski and Jendritzky 2002). For ex-ample, the difference of one degree centigrade around thirty-five de-grees centigrade seriously affects the possibility of the heat-stroke. How-ever, the indoor thermal environment for new or renovated projects are not still satisfactory for some owners. This is partly because the indoor thermal design is not usually performed in a very efficient manner be-tween owners, landscape designers, and thermal designers.

One reason for the inefficiency issue is that architectural design process is usually divided into multiple processes, such as landscape design, facility design, and structure design. Accordingly, the architectural design data is not centrally managed among all professional designers. In addition, the difficulty to execute major design changes disturbs an efficient discussion. Recently, the Integrated Project Delivery (IPD) has been promoted as a new design process concept (Ghassemi and Gerber 2011). IPD is a concept for optimizing the architectural design process in which stakeholders, such as owners or designers, cooperate from the beginning to the end of the design project. Using Building Information Modelling (BIM) is essential for realizing IPD. BIM is a standard information model that hosts life-cycle data of the facility and will be utilized for the various simulations relating to the architectures such as the earthquake simulations. Hence, all the life-cycle data is required to be integrated with the BIM (Hiyama et al. 2013). However, Computational Fluid Dynamics (CFD) software applications, which are widely used as a tool to perform advanced thermal environment analysis (Hartog et al. 2000), are not integrated with the BIM. Especially, BIM models of architectural spaces are not utilized as the object domain in the CFD simulation (Lee and Song 2010).

Another reason for the collaboration inefficiency issue is that the visualization results generated by CFD software applications are not easy to interpret for none-professionals. The CFD results are usually heavy numerical data and it is difficult to comprehend them in relation with the 3D space, which affects the efficiency of discussions related to the thermal design. The results are generally visualized in 3D by the analysis software applications. These applications can analyse the CFD results in detail; however, they cannot visualize the models of the simulation objects realistically due to unrealistic lighting simulation or background scenes. Additionally, scenes can only be visualized in a third-person view. In order to solve these problems, the visualization of CFD results using a Virtual Reality (VR) authoring software application has been investigated by Hosokawa et al. (2016). Their research visualizes the CFD results in a photorealistic 3D space in a first-person view, and studies both thermal and landscape design. However, a VR environment created by Computer Graphics (CG) models are used for their study, which is disconnected from the real world and does not allow users to experience the real feelings of the environment. On the other hand, Augmented Reality (AR), which is a technology to augment the real world with digital information and media, such as 3D models and graphics, can replace VR to provide a more natural feeling of the environment for users. This technology has an advantage of being used in the real scene, such as existing rooms. Hence, CFD visualization using AR technology can be efficiently utilized for examining the outcomes of renovation projects (Yokoi et al. 2016).

Indoor greenery has been used in the buildings as a renovation meth-od of the thermal environment (Bregon et al. 2012). It is often used for providing a stress-relief environment because of the effect of the green colour; however, its effect on adjusting the thermal environment has been verified (Asaumi et al. 1994).

The research goal presented in this paper is to investigate a cooperative architectural design process of the thermal environment for realizing the IPD. A system in which BIM, CFD, and AR are integrated is developed to provide interactive

visualizations. In our proposed system, easy-to-comprehend visualization of CFD results augment the real scenes to provide users with information about thermal effects of their renovation design options. Case studies to assess the effect of indoor greenery on the thermal environment are performed. This paper focuses on the effect of the indoor greenery and the solar radiation on the thermal environment.

2. Methodology

In our proposed system, BIM, CFD and AR are integrated. It consists of five steps; creating the BIM model, mesh generation, boundary conditions setting, simulation using CFD, and visualization using AR technology. At first, BIM model of the architectures is created based on the design drawings using a BIM authoring software application. Next, the volume mesh is created based on the created model using mesh generation software applications. Boundary conditions are set manually based on the information of the model such as the heat flux of the wall and the amount of air-flow from the air-conditioner. In the simulation step, non-steady sate fluid simulation is executed based on the defined boundary conditions using a CFD software application. The simulation results are visualized using AR technology in the visualization step. The CG model of the simulation results augments the scenes of the real in-door environment in the AR environment. Details of each step are described in the following subsections.

2.1. CREATING BIM MODEL & MESH GENERATION

BIM model is created based on the design drawings using a BIM authoring software application such as Autodesk Revit Architecture. Based on the created model, the volume mesh is created using mesh software such as blockMesh and snappyHexMesh. First, the model is split to structured grids. Next, the grids are split in more detail around the objects, such as an air-conditioner.

2.2. BOUNDARY CONDITION SETTING & SIMULATION USING CFD

Boundary conditions are set manually based on the information of the model, such as the heat flux of the wall and the amount of air-flow from the air-conditioner. A radiation model is implemented to the solar model including the solar primary heat fluxes, the reflective fluxes on walls, and the diffusive sky radiative fluxes. The sky diffusive radiations for horizontal and vertical walls are calculated according to the Fair Weather Conditions Method from the ASHRAE Handbook (ASHRAE 2009). The information related to the solar direction such as Greenwich Mean Time (GMT), start date, start time, longitude, latitude, and the radiative properties such as emissivity, absorptivity, and transmissivity of the architectural components are set manually.

Thermal conditions of the indoor environment are simulated using a CFD software application such as OpenFOAM (an open-source CFD software toolbox). The thermal simulation is performed on the assumption that the fluid is non-steady state and turbulence flow. The CFD solver calculates the heat transmission using a coupled analysis of solid heat conduction and fluid heat transfer and solid-fluid heat transmission. Each region of solid and fluid are allocated from the grids cre-

ated in the mesh generation step. After executing the simulation, a post-processing activity using a visualization software application, such as Paraview, is performed to check the results.

2.3. VISUALIZATION USING AR

Simulation results are visualized using the AR technology. The AR registration methods are vision-based method (such as marker-based or marker-less-based) and location-based method. The display types are Head Mounted Display (HMD) and hand-held display. In this research, marker-based method with HMD is used because of its ease of use in indoor space, and a higher degree of provided immersion. The system visualizes arrows of the air-flow and heat-maps of the temperature on the scenes of the real indoor environment. The results are shown using cross-sections such as XY plane, YZ plane, and ZX plane. The 2D visualization planes are moved using an input device such as a gamepad controller.

3. 3. Case Study

The system data flow is shown in figure 1. The BIM model was created using Autodesk Revit Architecture 2016. The model is exported as IFC file, and imported to SketchUp 2016 and then exported as STL format. The volume mesh was generated using blockMesh software and snappyHexMesh software. The CFD simulation was executed using Open-FOAM (ver.1606+). The simulation results are exported as VTK file format, and imported to the Game Engine (i.e., Unity (Ver.5.3.2.f)). In the visualization using AR technology, CG models are visualized using Unity plugged-in Ovrvision Pro SDK. The Oculus Rift Development Kit 2 (DK2), an HMD equipped Ovrvision Pro, a USB 3.0 VR stereo cam-era are also used. The Oculus Rift DK2 is a video see-through typed HMD, and can secure a wide angle. The system was operated using Logicool f710 game pad controller.

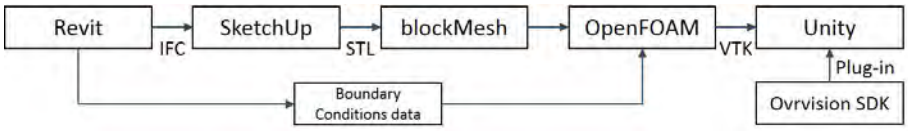


Figure 1. System Flow.

3.1. EXPERIMENT CONDITIONS

The validation experiments were performed in on the assumption of an office room in Osaka, Japan (North latitude: 34.822°, East longitude: 135.521°), with the following dimensions: 6.5 m (depth) × 4.3 m (width) × 2.6 m (ceiling height) as shown in figure 2. The test conditions are set at 14:00PM in January 27th in the winter and August 19th in the summer in Japan (GMT: 9). Solar direction is determined by the location, date, and time. The turbulence model was referred to k-epsilon turbulence model in which eddy viscosity coefficient is calculated using turbulent energy and turbulent disappearance rate. In this experiment, the window is facing south and receives the solar radiation. An AR marker (0.72 m (height) ×

0.72 m (width)) was set on the table in the centre of the room as shown in figure 1. A user wore an HMD and was placed near the entrance in order to have the marker in his field of view.

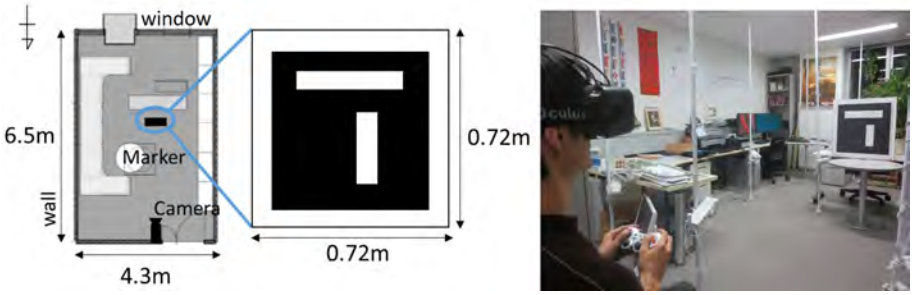


Figure 2. Experiment room: Floor plan (left), Actual photo (right).

A ceiling mounted air-conditioner with four cassettes is used. The boundary conditions of the architectural components were set including conditions related to the solar radiation such as emissivity, absorptivity and transmissivity (table 1). The boundary conditions of the air-conditioning unit including flow rate, velocity, and temperature were set based on values that are shown in table 2.

Table 1. Boundary Conditions (Architectural Components).

		Wall	Ceiling	Floor	Window
Heat transmission coefficient [W/(m^2·K)]		1.38	1.80	-	5.60
Indoor wall temperature [°C]		20.0	20.0	20.0	20.0
Outdoor temperature [°C]	**Winter**	11.0	20.0	20.0	11.0
	Summer	38.1	20.0	20.0	38.1
Emissivity		0.700	0.700	0.700	0.113
Absorptivity		0.700	0.700	0.700	0.113
Transmissivity		0.010	0.010	0.010	0.815

Table 2. Boundary Conditions (Air-conditioner).

		Supply	Return
Flow rate [m^3/min]		18	18
Area [m^2]		0.06×4	0.36
Velocity [m/s]		2.5	1.2
Temperature [°C]	**Winter**	24	-
	Summer	22	-
Supply angle [°]		60	-

3.2. EXPERIMENT CASES

The experiments with the air-conditioner were performed in winter and summer with the following settings: (a) no greenery (b) wall side with greenery (c) window side with greenery (d) wall side & window side with greenery. Additionally, the experiments without the air-conditioner were performed in winter and summer: (e) no greenery (f) wall side & window side with greenery. The boundary conditions of each component with greenery are shown in table 3.

Table 3. Boundary Conditions (Components with Greenery).

	Wall with greenery	**Window with greenry**
Heat transmission coefficient [W/(m^{2}·K)]	1.30	4.43
Emissivity	0.408	0.101
Absorptivity	0.408	0.101
Transmissivity	0.009	0.089

3.3. RESULTS

The simulation results of temperatures in the cases with the air-conditioner are shown in table 4 (in winter) and table 5 (in summer). The average temperature for the case (d) was higher than the case (a) in winter, and the case (d) was lower than the case (a) in summer.

Table 4. Simulation Results (cases with the air-conditioner in winter).

Winter	**(a)**	**(b)**	**(c)**	**(d)**
Maximum [°C]	23.977	23.977	23.977	23.977
Minimum [°C]	21.643	21.656	21.669	21.682
Average [°C]	22.442	22.453	22.445	22.456

Table 5. Simulation Results (cases with the air-conditioner in summer).

Summer	**(a)**	**(b)**	**(c)**	**(d)**
Maximum [°C]	36.041	36.028	36.048	35.881
Minimum [°C]	22.042	22.042	22.042	22.042
Average [°C]	33.827	33.814	33.833	33.694

The simulation results of temperatures in cases without the air-conditioner are shown in table 6. The average temperatures of the case (f) were higher than the case (e) in both winter and summer. In the summer, the case (f) were 0.983 °C higher than the case (e).

Table 6. Simulation Results (cases without the air-conditioner).

	Winter		Summer	
	(e)	(f)	(e)	(f)
Maximum [°C]	17.931	17.996	38.522	39.557
Minimum [°C]	17.563	17.659	38.485	39.402
Average [°C]	17.761	17.848	38.506	39.489

The visualization results of cases with the air-conditioner in winter are shown in figure 3. The arrows of air-flow and heat-maps of temperatures were overlaid on real world scenes, and the greenery model was overlaid along the actual wall or window. The colours of heat-maps were distributed from blue to red, and the colours near the air-conditioner were almost red. The directions of the arrows were almost downward due to the blow from the air-conditioner.

3.4. DISCUSSIONS

For the case (a) in winter, simulation results were compared with the actual temperature values. The actual temperatures were measured in 36 points in the room (depth: 1.60 m, 3.85 m, 6.1 m × width: 1.1 m, 2.1 m, 3.1 m × ceiling height: 0.3 m, 0.9m, 1.5m, 2.1 m). The average of the actual temperatures was 23.65 °C, which was 1.2 °C higher than the simulation result. Considering case studies with the air-conditioner, the temperature of cases with greenery was higher than cases without green-ery in the winter, and vice versa in the summer. The reason is that the greenery supressed escaping of heat outside the room from the air-conditioner, that is, the warm air from the air-conditioner was saved in winter and the cool air from the air-conditioner was saved in summer. Considering the case studies without the air-conditioner, the tempera-tures of cases with the greenery were higher than the cases without the greenery in both winter and summer. The actual survey by Asaumi et al. (1994) shows that the indoor greenery increases indoor temperature. This is because the effect of the greenery affects the heating up of the greenery surface rather than solar shading. Although the solar radiation directly reached to the floor and walls through the window in the cases with no greenery, the heat transmission coefficient of these surfaces were lower, and hence the amount of the sensible heat from these surfaces did not greatly affect the indoor air. The differences of the temperatures between cases with greenery and cases without greenery were not significant. The reason is that simulations in this study did not consider the transpiration of the greenery due to the limitations of the simulation software application.

The accuracy of the AR registration was verified by comparing the actual position of objects with the location of the augmented 3D model. The horizontal and the vertical errors were calculated in 10 different photographs. The results show that the maximum error was 18.14 pixels and the minimum error was 12.64 pixels, and the average of the horizontal errors and the vertical errors were 6.78 pixels and 13.80 pixels, respectively. One of the reasons for the error is the image-capturing problem of the camera. The camera on the HMD was always slightly moving, or was not stable because of the vibration. Additionally, the lighting condition and the distance from the marker may affect the accuracy.

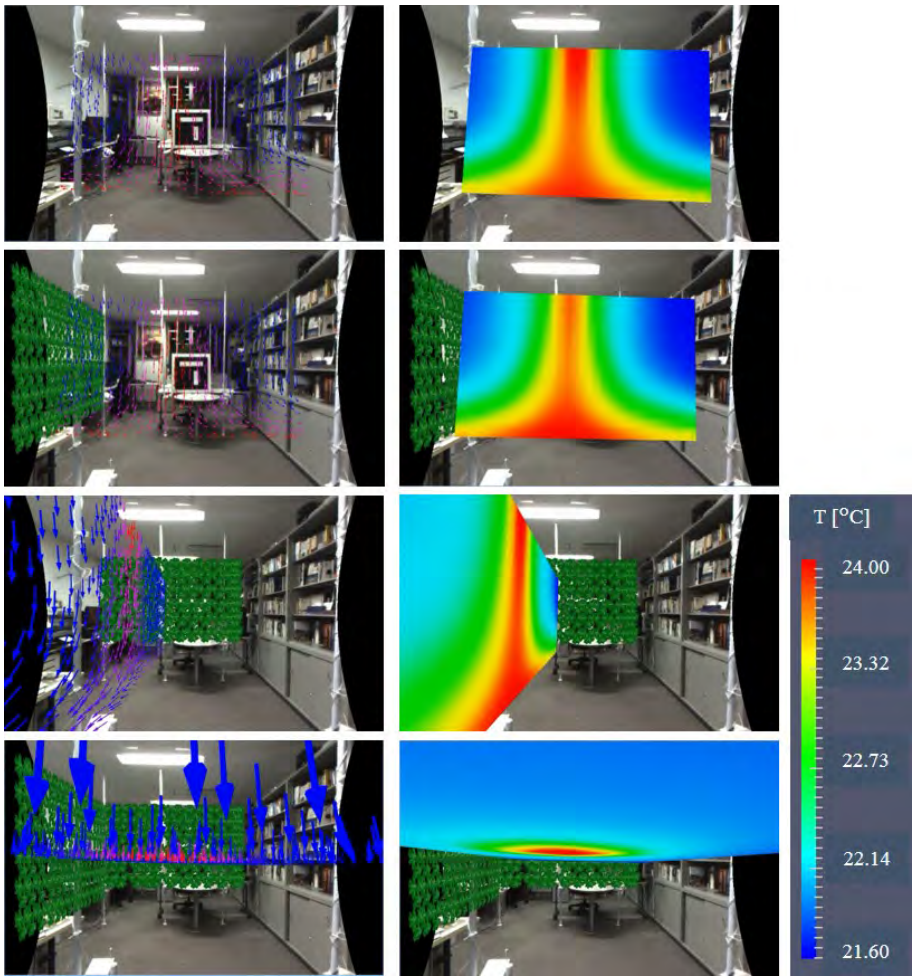


Figure 3. Visualization Results: Air-flows (left), Temperatures (right).

4. Conclusions and Future Work

This research developed a system in which BIM, CFD, and AR are integrated to assist a cooperative architectural design process of the thermal environment. The BIM model was utilized together with the CFD simulation considering the solar radiation. The results of the CFD simulations were visualized with arrows and heat-maps using the AR technology. Case studies were performed for the renovation projects with indoor greenery, and the simulation results were compared with cases with no greenery. The thermal results and the greenery model augmented the scenes of the actual room when using the prototype system.

This system contributed to facilitating the cooperative architectural design process especially between owners, landscape designers and thermal designers. In-

tegrating BIM and CFD helps realizing IPD. Additionally, integrating CFD and AR provided users, such as owners and landscape designers, with a more natural feeling of the thermal environment. The case studies showed that both landscape design study and thermal design study could be performed at the same time.

As future work, more detailed settings, such as the transpiration of greenery, should be performed for more accurate CFD simulation. Additionally, it is expected to simulate and visualize other factors such as air quality or sound insulation for more extensive renovation studies. The case studies should be performed in larger spaces and for other scenarios such as demolition of a wall. Using markerless AR, such as location-based method or method that uses natural feature points, will be required to realize a walk-through for users in larger spaces.

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OUTDOOR MARKERLESS AUGMENTED REALITY

A System for Visualizing Building Models Using Simultaneous Localization and Mapping

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Abstract. In this study, an Augmented Reality (AR) system is developed to be used for visualizing design projects of buildings. In such design projects, it is desirable to enable design stakeholders visualizing the outcomes of different design options to reduce the resistance and hesitation towards new design challenges. The research proposes an outdoor mark-er-less AR using Simultaneous Localization and Mapping (SLAM) for the AR tracking. Our proposed system performs reconstruction and localization steps in real-time, as opposed to similar methods in which the reconstruction step is done offline. A case study has been performed for a de-sign scenario of buildings. The case study verified the performance of visualization and tracking.

Keywords. Architecture and urban environment; Augmented Reality (AR); Simultaneous Localization and Mapping (SLAM); Visualization.

1. Introduction

In recent years, redeveloping or renovating existing buildings has become common to improve visual landscape, which is important in enhancing our quality of life. The need for visual landscape assessment of large-scale projects to evaluate the impact of projects on the surrounding landscape is increasing. In such projects, owners can actively participate in the design of new functionalities or interior setup. While it may be easier to grasp the complete image of a new construction for professionals, it may be difficult to envision the outcome of a design or renovation project for laypeople. Hence, there is a need for a method to visualize design outdoors as well as to communicate and to share idea between designers and non-professional.

Augmented Reality (AR), which can visualize the design can be a solution to the problem and is becoming common in architectural and urban development fields (Reitmayer et al. 2006; Karlekar et al. 2010; Schubert et al. 2015). AR overlays images or 3D virtual objects on real world images with computer generated data using video or photographic displays. AR can help visualizing full-scale building projects at the planning or design stage before the actual construction and can be used to visualize some properties of the building. AR is similar to the Virtual Reality (VR) technology. However, VR needs to have not only the design objects but also the surrounding buildings. Conversely, AR can use surrounding objects and context from live video images resulting in saving time and cost. In a VR scene, special devices are needed, such as controllers to operate viewpoint or 3D movements. However, in an AR scene, this operation can be realized by a camera for more intuitive operation.

In this study, an AR system is proposed for the use in outdoor environments specifically for visualizing design outcomes for buildings at the design stage. In comparison with other design study meetings in a conference room, our system enables non-professionals to check building information, such as 3D virtual objects, by integrating full-scale models at the planning or design site. To realize this, our system is required to be operable outdoors by people who are not fully familiar with Information Technology (IT) tools.

To use the AR technology in this context, a big challenge is to realize it outdoors with a high precision for registration and a robust tracking. The accuracy mainly depends on the geometric registration with the live video and 3D virtual models. To solve this registration issue, relationships among positions and postures of users, and positions of drawn 3D objects should be identified by an AR system. The reference point of geometric registration is the sensor position in sensor-based methods (with physical sensors such as GPS sensor, gyro sensor, acceleration sensor), or the position of artificial markers in marker-based methods, which is one of the vision-based methods (Yabuki et al. 2011). In the sensor-based methods (Watanabe 2010), registration accuracy depends on sensors' performance. In an urban area, it is known that GPS sensor's accuracy is not high because of high-rise building.

Meanwhile, in the marker-based method, it is possible to position a 3D model near a marker by using a large-scale marker for visualizing an outcome of buildings. This method is relatively easy to implement; however, the camera needs to constantly capture the marker, which brings limitations for the users' movability and challenges related to the installation of large markers.

Therefore, marker-less AR system that does not need artificial markers has been developed. The conventional method of marker-less AR systems relies on natural features of the image from the live video. The position and posture of a 3DCG model are decided according to these natural features. However, the natural feature, which is used for geometric registration, needs to be always captured by the AR camera. Using point clouds for detecting natural features is another option, such as the research by Yabuki et al. (2012); however, the system needs special equipment, such as 3D laser scanner, to detect these point clouds. Some research realized marker-less AR using Structure from Motion (SfM) technique, which can

reconstruct 3D shapes from photographs of plural viewpoints (Dellaert et al. 2000). However, AR systems using SfM (Frey et al. 2013; Sato et al. 2016) have specific limitations. For example, there is a time lag between the process of point cloud reconstruction and the process of system use.

In contrast, as another 3D reconstruction technique, Simultaneous Localization and Mapping (SLAM) (Leonard et al. 1991) is attracting attentions. SLAM can realize 3D reconstruction in real time (Martin et al. 2014). Some Head Mounted Displays (HMD), such as Hololens, use SLAM-based tracking method. However, these kinds of displays have problems in outdoor use. First, full-scale building cannot be visualized on a display with an HMD because the area of the display is narrow. Field of view of such displays are also small. Second, resolution of HMD is still low. A low-resolution image of a building design could lead to users' misunderstanding.

In this study, a marker-less AR system is developed based on visual SLAM to realize a robust outdoor tracking with free movement. The proposed system uses a camera on an android tablet to execute vision-based tracking.

2. Methodology

Our proposed system for visualizing the design of a building runs on an android tablet or a smartphone and our tracking method is based on visual SLAM. It consists of four steps; creating a 3D model, initialize the position and rotation of augmentation, tracking, and visualization using AR. At first, a 3D model of the building is created based on design drawings using a 3D modelling software application. Secondly, the position and rotation of 3D models are initialized by inputting geometric coordinates to the system. In the tracking process, the system tries to find features in surrounding environment and to localize the position and identify the rotation of the camera. Finally, each frame is augmented.

2.1. 3D MODEL CREATION

3D models of the architectures are created by software applications such as 3D modelling software or BIM authoring software applications. The created 3D models are converted into a highly versatile format such as fbx.

2.2. INITIALIZATION OF AUGMENTATION

To localize the 3D models, coordinates that are measured in advance are used. In the conventional AR, it is possible to acquire the registration reference points before running the system. For example, in marker-based methods, the position and the orientation of the augmentation are defined based on markers. In sensor-based methods, the geographic coordinates, which are obtained by the GPS sensor, are used for the alignment. However, in our system, since the reference points used for the registration are generated in real-time, it is not possible to define the registration points in advance. Meanwhile, the registration in this study does not necessarily start from free viewpoints. Visualization of the augmentation by the AR can be registered from a fixed viewpoint since the proposed system is for a design study of buildings. After determining the viewpoints, the position and pos-

ture between the viewpoints and the 3D model to be rendered are measured. Next, the position coordinates and the angle of the rotation are input to the system. In addition, it is necessary to match the coordinates system used in our system with the coordinate system of the screen projected by the AR camera at this time.

2.3. TRACKING METHOD BASED-ON VISUAL-SLAM

In this research, the tracking method is based on SLAM. SLAM is a technology that is mainly used in the field of robotic engineering. With SLAM, it is possible to estimate the position of the robot and perform environment mapping at the same time. In recent years, SLAM has been extensively studied from basic research level to practical application level in the industry. As an extension of SLAM, visual SLAM that performs SLAM processing with a camera or cameras instead of sensors has been investigated. The advantage of AR using visual SLAM compared to other vision-based AR is in its real-time processing. In the AR using visual SLAM, the registration and generation of reference points used for registration are performed at the same time. In the marker-less AR using SfM, there is a time lag between preprocessing to reconstruct point cloud of an environment and real-time processing to draw augmentations (Bae et al. 2013). Therefore, the change in the illumination condition and shadows affect the accuracy of alignment and tracking outdoors. However, since there is no time gap between point cloud reconstruction and real-time processing in SLAM, these effects are limited. Basic processing of visual SLAM is as follows:

1. Tracking a set of feature points through successive image frames
2. Triangulation for projecting points used for tracing to the 3D space
3. Estimating the tracking point after a movement to estimate the camera position and orientation

2.4. SYSTEM IMPLEMENTATION

In this study, the proposed system was implemented using a game engine, C # programming language, and System Development Kits (SDK). To create a 3D model of a building, Autodesk Revit Architecture 2016 was used. Unity 3D (Unity 5.4.0) was used as the game engine. Unity is a cross-platform game engine and it provides advanced real-time rendering. To realize marker-less AR with SLAM, KudanAR (ver. 1.3), which supports marker-less tracking based on visual SLAM, was selected. The tracking method is called as arbitrary tracking which provides instant SLAM. C # was used for writing scripts in Unity3D. The developed system was applied to Nexus 9 (Android.5.1.1).

3. Case Study

To verify the applicability of the proposed system for a design project, a case study was conducted outdoors. The case study was carried out at Osaka University Suita campus.

3.1. EXPERIMENTATION

For a design review case study, a design of a house is selected. Using the developed system, users can review design of a house by changing the rotation of the house. A sample photo of the experimental scene is presented in figure 1 and figure 2.



Figure 1. Experimentation area.



Figure 2. Tracking route and the initial viewpoint for experimentation.

The procedure for the verification study is presented in the following steps:

1. A 3D model of a house was created in Revit 2016 (figure 3). Although the Revit model can be directly exported to Unity, the coordinate system will be changed

during the export process. In order to preserve the original coordinate system of the 3D model, Autodesk 3ds MAX 2016 was used. The model is exported to 3ds MAX using .fbx file format and exported to Unity using .3ds format. As the scale of the model changes in the process of conversion, it is necessary to adjust it.

2. To initialize the position and rotation of the 3D model, the position coordinates and the angle rotation were inputted to the system. These coordinates were obtained by measuring the distance between a predetermined viewpoint and the drawing position of augmentation. Users can perform the registration from a fixed viewpoint in accordance with the map displayed on the screen. This map helps users to visually understand where to start the system.
3. Once the 3D model is placed, the tracking process starts with visual SLAM.
4. The application of the developed marker-less AR system for building design is verified.

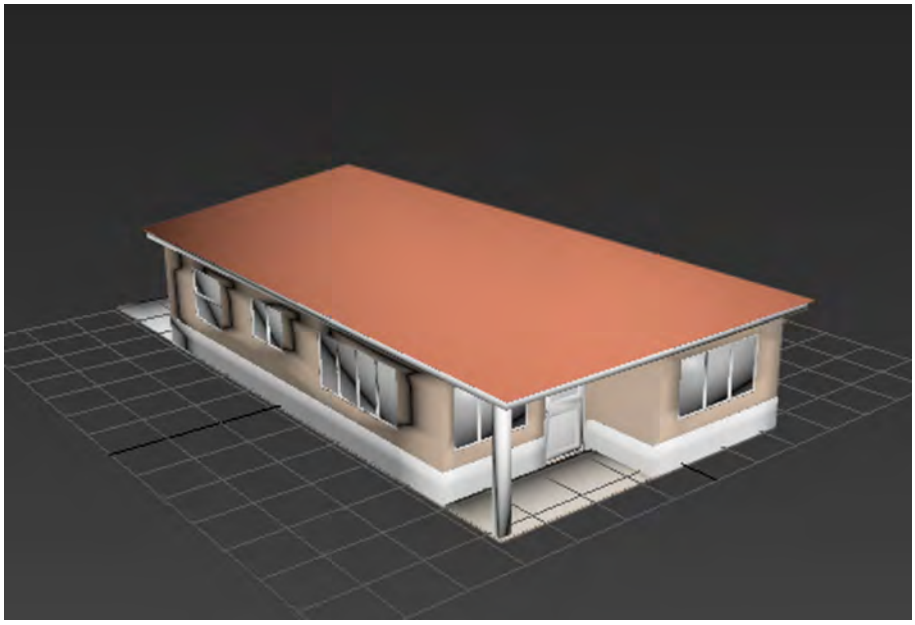


Figure 3. 3D model of a house.

3.2. RESULTS

This experiment demonstrates that outdoor marker-less AR system can be used with an android tablet. Figure 4 shows a set of sample outputs of the initialization. The fixed viewpoint for the AR and the current position of the user are displayed on the upper right side of the screen. The blue circle indicates the GPS sensor position considering its error. Figure 5 shows a set of sample output of tracking. Along with the movement, a slight blur in the model will occur; however, the outdoor tracking was confirmed.



Figure 4. Results of augmentation.



Figure 5. A set of tracking outputs.

Figure 6 shows a design alternative that rotated the house model by 45 degrees. In the tracking process, when the user walks into the house, the position of the virtual user in the VR space also moves into the house. The view from the interior of the house is also verified in the experiment (figure 7).

The experiment verified that the system is able to perform registration, tracking using camera, changing the angle of the house and walking inside the house. Additionally, in comparison with other marker-less AR system using natural features, the proposed system was less susceptible to the changes in outdoor illuminance.

3.3. LIMITATIONS

In the proposed system, the initial position and rotation of the 3D model are acquired by measuring the distance and the angle between fixed viewpoints and the augmentation object. These values are converted into the coordinates system used in the system, and the user inputs them to the system in real-time processing. However, these coordinates are different for each use. This is because the position and orientation of the android tablet are not stable because of height and eye level difference for each user. Therefore, in order to actually perform nominal positioning, it is necessary to fix the tablet with a tripod.



Figure 6. Alternative plan for the building placement.

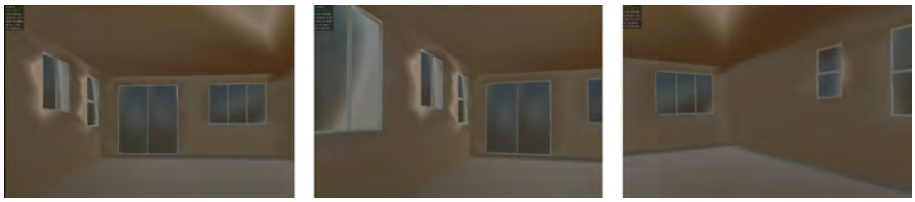


Figure 7. View from inside the building.

The size of the 3D model of the building is limited. In the tracking process, the system estimates the current position and the orientation of the camera while finding features of an environment surrounding the camera. These points are generated based on the ground and walls. However, for example, for drawing a skyscraper in AR, in the case of a near view, it is necessary to look up at the building in order to confirm the overall appearance of the building. Along with looking up at the building, the ground and wall disappear from the screen and the area of the sky increase, making it difficult to find trackable points in the scene.

There are also problems related to camera's movement. Our system has a robust tracking with camera move such as pan and tilt. However, the system easily loses sight of trackable features when dallying or moving around the house. If a system user moves a few meters, errors in the position, orientation and the scale of virtual objects become larger.

4. Conclusions and Future Work

In this research, an outdoor marker-less AR system using visual SLAM was developed for an intuitive and realistic study on the planning and the design of buildings. The developed AR system has been verified in a case study. In the case study of visualizing a house, which is assumed to be placed in Osaka University Suita Campus, registration, tracking, changing the angle of a building and walking inside the 3D model of the house were verified.

This system contributes to the field of architectural design by realizing intuitive design study by visualizing the model of the building outdoors. In order to use the system; even if fixed viewpoints are defined, complicated and high cost pre-processing are not necessary. In the tracking process, the system showed the possibility of walkthrough inside the building.

As future work, it is necessary to conduct detailed precision verification experiments for the tracking process. A comparison of the robustness of the tracking of the development system with the other AR system should also be performed.

Acknowledgement

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CAMPUS SPACE MANAGEMENT USING A MOBILE BIM-BASED AUGMENTED REALITY SYSTEM

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Abstract. In South Korea, the changing paradigm of family composition toward single-person households and nuclear families has caused the decrease in number of students, which has led to the need for change in the qualitative, rather than quantitative, management of spaces and facilities on university campuses. In particular, since 2005, the merging of universities have accelerated, which has brought up the need for a system that facilitates the management of integrated university systems. Accordingly, universities now require efficient system operation based on three-dimensional and data visualization, unlike the document-based management of facilities and spaces in the past. Users lack a sense of responsibility for public facilities, causing difficulties such as energy waste and frequent movement, as well as damage and theft of goods. This study aims to form an AR-based interface using the ANPR algorithm, a computer vision technique, and the position-based data of the GPS. It also aims to build a campus space management system to overcome the limitations of current systems and to effectively and systematically manage integrated building data. In addition, for module test verification, the prototype is applied to actual campus spaces, and additional demands for campus space management in the AR application are identified and organized.

Keywords. Augmented reality; Campus space management; BIM; CAFM (computer-aided facilities management); user experience (UX).

1. Introduction

In South Korea, the changing paradigm of family composition toward single-person households and nuclear families has caused the decrease in number of students, which has led to the need for change in the qualitative, rather than quantitative, management of spaces and facilities on university campuses. In particular, since 2005, the merging of universities have accelerated, which has brought up the need for changes in college education. For this reason, universities are not in

the position to insist on perpetual expansion of spaces and facilities, and now require efficient system operation based on three-dimensional and data visualization, unlike the document-based management in the past.

Due to the characteristics of universities, the management of facilities of on-campus spaces requires periodical review every six months. Also, users lack a sense of responsibility for public facilities, causing difficulties such as energy waste and frequent movement, as well as damage and theft of goods. In addition, log data such as information on entries and exits may be obtained for effective utilization in space management, but they are treated as volatile data, and are not utilized. Such data are built into existing space management systems, but there are difficulties in obtaining effective information on the site situation. Therefore, this study intends to build a BIM (Building Information Modelling)-based campus space management system by applying the technology of ANPR (Automatic Number Plate Recognition), which is a vision algorithm, and position-based data of the GPS (Global Positioning System) to an AR (Augmented Reality)-based interface environment. The goal is to overcome the limitations of current campus space management systems, reduce inefficient budget investment, and manage integrated building information more effectively and systematically.

1.1. RANGE AND METHOD OF RESEARCH

This study is on the development of a system for more efficient campus space management by applying the technology of ANPR, which is a vision algorithm, and position-based data of the GPS to an AR-based interface environment, and was focused around Hanyang University.

The research proceeded in the following method.

Firstly, the introduction examines the study's background, purpose, range, and methods.

Secondly, the current state of space management systems are theoretically examined, and the concept and characteristics of AR are explained. Then, the characteristics and necessity of AR in campus space management are identified.

Thirdly, in order to build a space management system that utilizes the ANPR algorithm and GPS data, the methods of visualizing data applicable to AR, building BIM-based data, and developing a mobile application are examined.

Fourthly, a structure is established for a campus space management system and a prototype is built and applied to Hanyang University, verifying the system.

Lastly, the significance of this study and its limitations in the process are presented for future research.

2. Theoretical Analysis

The inspection team, management team, energy manager, and asset manager of Hanyang University, which is the subject of application for this study, were interviewed. It was found that not only the current floor plan, space, energy, and asset information of each building are managed by different databases and teams, but there was also no single integrated model or system that had been built.

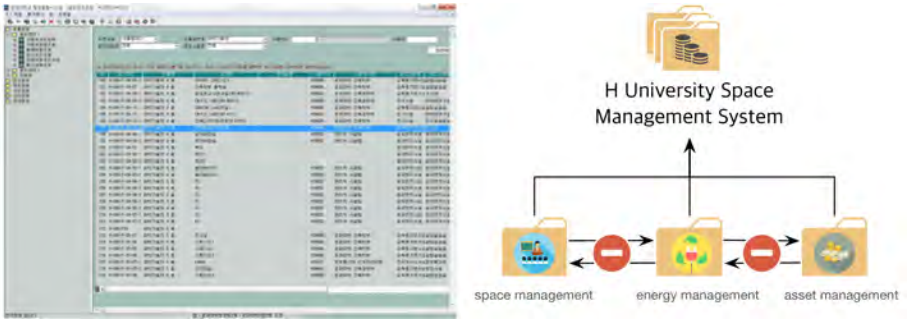


Figure 1. Administrative management system of Hanyang University.

As shown in figure 1, the database of Hanyang University's overall space management system was founded on two-dimensional graphic information and text, and was managed by being dispersed into three aspects: 1) space management, 2) energy management, 3) asset management. There was no single integrated system for the database managed in this way, and the information was stored as Excel files.

The greatest difficulties for managers were: 1) Difference in information between the site and in the office, and having to manually rebuild the situation and information changing on site, 2) absence of a single integrated system and organized management system, 3) budget issues that increase every year, 4) lacking sense of space privatization of managers and users, and 5) lacking manpower capable of using the system. These five items were chosen. Also, the necessity of building an additional system was being recognized, but there were opinions that additional costs and manpower investment were burdensome.

2.1. CONCEPT OF AR

AR (Augmented Reality) is a field derived from VR (Virtual Reality), the research on which was begun by the development of the see-through HMD (head-mounted display) by Ivan Sutherland in 1968. In VR, the user generally is immersed in a virtual environment, so the user cannot see the actual environment, but in AR, the user can see actual surroundings, where the actual environment and virtual objects are blended. In other words, VR shows the user a replacement of the actual world, but AR is different in that it shows the user the actual world supplemented with virtual information by synthesizing virtual objects into the actual world, and has the feature of providing the user with a better sense of reality compare to VR.

According to Milgram, the greatest difference between VR and AR is the degree of approach to reality.

The Real Environment is the reality in which we currently live and exist; Augmented Reality is the synthesization of virtual information based on reality; Augmented Virtuality is the synthesization of reality based on virtuality; and Virtual Reality is the design of figures and graphics using the PC. The range of these concepts altogether is referred to as "Mixed Reality."

The application of the ANPR algorithm and GPS data technologies on the AR interface is presented in figure 2.

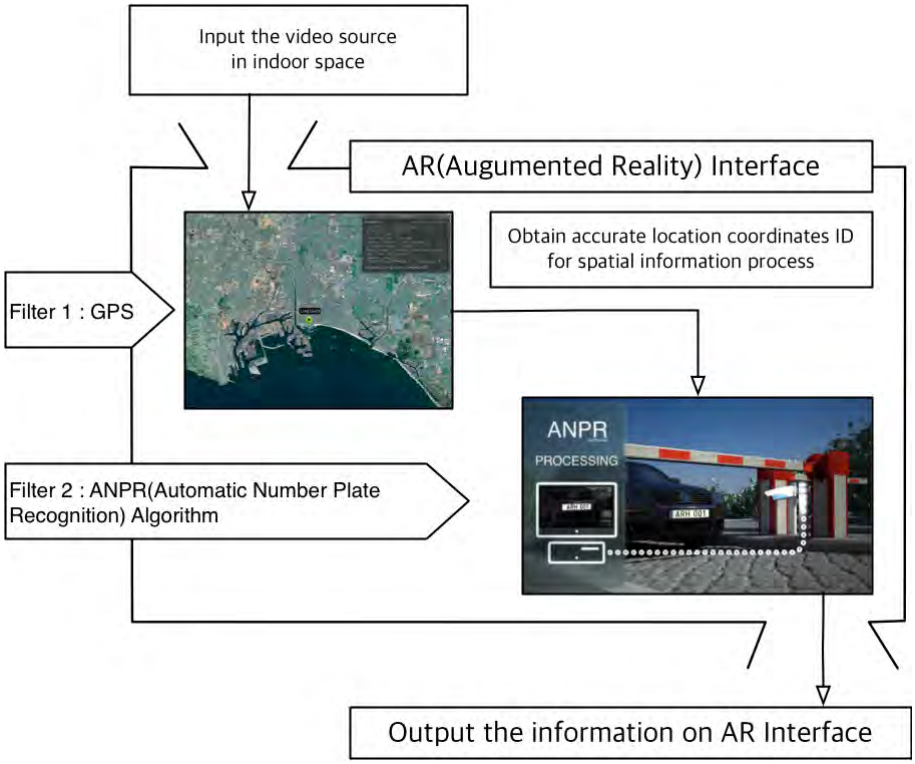


Figure 2. The Application of ANPR Algorithm and GPS Base Information Technology within the AR Interface.

The ANPR algorithm is also known as the vehicle license-plate recognition algorithm, and must go through the process of machine learning in order to recognize numbers and character information. The numbers and letters must have the same font style for better rate of recognition. The process of machine learning is a process that raises the system's rate of recognition by repetitively learning character data through all cases. If the numbers and letters have different font styles, a repeated DB operation is required for recognition.

2.2. ROLE OF AR IN CAMPUS SPACE MANAGEMENT

In this study, an AR interface is presented as a response to the current limitations of campus space management, and the space management data that can be actualized with AR is built with the following four types of data.

First, spatial data can be utilized. With spatial data utilization, system users, such as the administrator and manager, can obtain information of each room with a mobile device without a separate document or equipment on site, and correct errors. In addition, the administrator can access information on rooms that are being used incorrectly or without approval, which can even have an effect on on-campus safety.

Second, energy management data. Energy management data is generally maintained by being divided into the three areas of city gas, electricity, and water supply and sewerage. The place of use, purpose, used amount, and cost are managed for these areas, and energy management data have been in the form of volatile data. These data can be visualized, and with plots, the comparison of energy usage among different rooms, comparison of usage to the previous month, and target energy reduction can be digitized to change members' awareness and reduce inefficient use of budget. Also, real-time energy usage can be checked to prevent safety accidents such as blackouts and fires in heating and air conditioning systems.

Third, entry and exit data. Entry and exit log data are generally also managed as volatile data, which the campus has been unable to create added value with. However, by visualizing entry exit data using AR can have the effects of 1. Efficient space distribution, 2. Prevention of unnecessary space expansion, and 3. Theft prevention. The "Policy Study Report of 2008" by the Ministry of Education states that the greatest reason of difficulty in efficient space utilization on campus is the friction among campus members. The amount of usage in each room for each time frame can be visualized into a plot, which can be utilized as objective evidence.

Fourth, asset information. The asset information of each room is compiled by the manager of each area, who checks each room every six months, and the final document is written up by integrating this information. However, documents that are distributed/overlapped in a small scale in this way lack reliability, and contain many errors with respect to the actual site. If the asset information for each room is visible in real time using AR, and if it can be edited immediately, these errors can be diminished, and there will be less of a need for a large amount of manpower.

3. Building a Space Management System Utilizing the ANPR of the AR Environment and GPS-Based Technology

In order to apply the prototype to Hanyang University, this study developed the concept by applying the ANPR algorithm to the school's room numbers. Afterwards, the data dispersed across each area were integrated and a server was made to manage them. The four types of data that were applied to the AR interface are: 1. entry and exit data for each room, 2. energy management data, 3. asset management data, and 4. construction data for each room. The database applied to the server was stored as an Excel file as shown in figure 3, but it was converted into a JSON file to make the data lightweight. The JSON file was uploaded to the server and synchronized with the system.

3.1. BIM DATA CONSTRUCTION USING GPS-BASED POSITION DATA

Hanyang University's building information is organized into a CAD file. A building with four floors underground and 7 floors above was selected, the model data for which was constructed using Autodesk Revit 2016. This allows for easy editing and changing of the geometric and non-geometric data on space, which is a merit of BIM. Not only that, but the BIM data is systemized into a DB, so that by setting the ANPR and GPS as the trigger, the data required by the system can be obtained from the BIM model. The data for each room can be extracted from the

BIM data. The room data required by the server, in which data is stored, is sent in the form of the room's space management data by synthesizing the room number and GPS data via ANPR. Figure 4 shows the constructed BIM.



Figure 3. Hanyang University space management data.



Room Number	Spatial Code	Staff	Level	Access Number	Energy	Fee per Month
FTC-1122	F-11-04-22	Public	11st. SL	12	297kW	$27
FTC-1123	F-11-90-23	8	11st. SL	24	536kW	$42
FTC-1124	F-11-12-24	10	11st. SL	14	352kW	$35
FTC-1125	F-11-90-25	7	11st. SL	30	2500kW	$96
FTC-1126	F-11-02-26	4	11st. SL	23	1250kW	$45
FTC-1127	F-11-12-27	Public	11st. SL	10	235kW	$23

Figure 4. BIM Model Building and Space Information.

The position data of the building's room can be obtained by finding the building's ID number through Batchgeo, a service for GPS utilization. The GPS position data can clearly recognize the current user's two-dimensional information within a small error range, but cannot grasp the information according to vertical variations with respect to different floors. Therefore, the room number according to the ARPN is captured through a camera image, and then the information on the floor number is also found and extracted, after which the building information is transmitted to the server together. These two types of data are stored as an Excel file, which must be saved as a CSV file, converted back into a JSON file, and transmitted to the server. Next, the latitude and longitude values of the mobile device are extracted from its LBS (location-based service) through GPS, and when the room number is tagged, the current location data is transmitted to the server. The server then sends the building information corresponding to the location of the tagged mobile device back to the mobile.

3.2. MOBILE APPLICATION UTILIZATION

The server is responsible for connection to a network that has a different role from monitoring and controlling the entire network, such as printer control and file management. Then, the server performs service according to the client's request, and plays the role of operating in the form of distributed processing that mutually inputs one or more application programs. Generally, it plays the role of managing information on the internet, and the server provides information by the request of the client. That which processes the information provided is the client. To effectively apply the system structure of this study, the mobile device equipped with sensors for GPS and ARPN application along with a camera becomes the client.

Basically, for the system in this study, the GPS and ARPN are synthesized in 1. The JSON file of non-geometric data and 2. BIM-based geometric data, synchronizing the geometric and non-geometric data, in order to construct an AR space management system that utilizes LBS.

Based on this, the UI implemented in the mobile device is shown in figure 5.

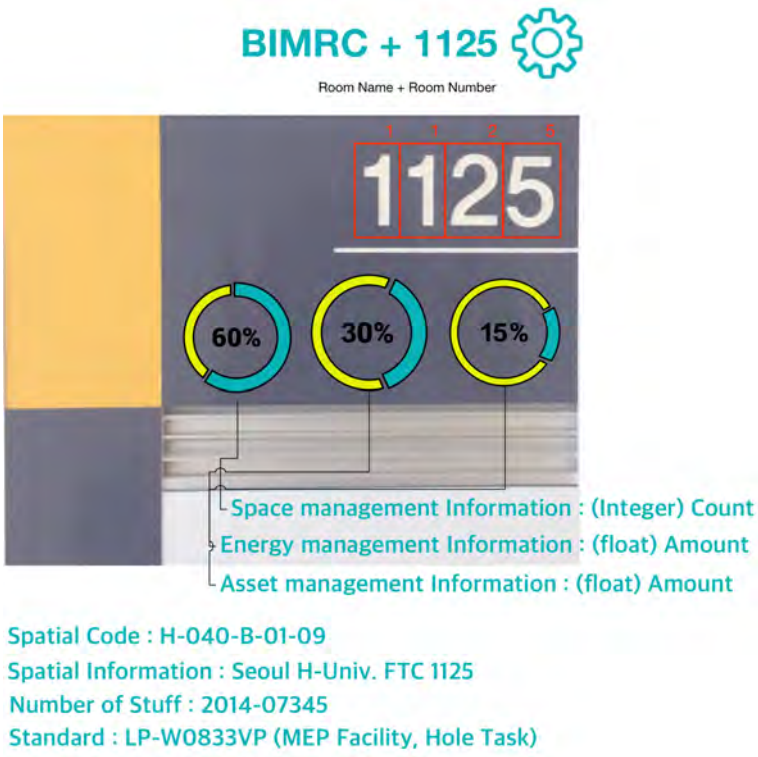


Figure 5. UI interface for the AR system.

4. Campus Space Management System Utilization

The application built in section 3 is installed and run on the user's mobile device. When a room number is scanned in front of a room corresponding to space management, a virtual grid is formed with the corresponding room number plate as the reference point. The constructed space management information is implemented in the AR interface using Unity 3D and OpenGL, and the user's vertical and horizontal location data is found. Here, the horizontal data is the location information using the GPS, and the information of the building that the user is currently located in is temporarily stored in the mobile device. Then, considering that GPS does not recognize altitude, the vertical data, the room number, and the information of the corresponding floor recognized by ARPN, are grouped with the horizontal data, which is transmitted to the server from the mobile device. Finally, in the server, the space management information corresponding to the room for which the location data was received, using the received vertical and horizontal data values, is presented in the AR interface. Figure 6 shows the overall framework of the system.

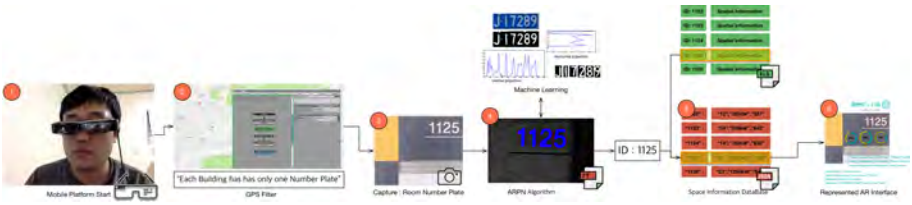


Figure 6. AR Space Management System Framework.

4.1. SYSTEM UTILIZATION

In this study, the room on the eleventh floor of Hall A and the fourth floor of Hall B of Hanyang University, the subject of this study, were selected as the target places of space management. An experiment was done on the implementation of AR by bringing the management information of Room 413 on the fourth floor and Room 1125 on the eleventh floor of different buildings from the server. First, the management target is identified, and the user runs the mobile application at the location of management. At the beginning of the execution of the program, the camera screen appears, and the room number is scanned. When the room number is scanned, the data values that track the current position are computed, and the information of the room that is about to be managed is displayed, and the manager checks the input/output information, as well as the energy and asset data. Then, if there is incorrect information, a part to be edited, or new information to be added, the setting modifies the data in real time. The information is then automatically updated by the server, which then synchronizes the mobile device. In the same order, when moving to the next place for management, and the room number is tagged again, the information corresponding to the place is managed.

5. Conclusion

This study developed a space management system for a university campus that uses LBS and AR technologies, and constructed a prototype by applying this system to the rooms of different buildings of Hanyang University. Based on this, the following conclusions can be drawn.

First, it overcomes the limitations of existing campus space management systems, and enables efficient and intelligent building management through systematic management of building information. In addition, it cuts unnecessary budgets, and is much faster and efficient to exchange and manage modified information.

Second, the study proposed the means to support an intuitive and natural building information search method by introducing it into the building management system in the AR interface environment. Most of the information implied in the space is not readily apparent to the naked eye. However, if the building information is expressed in the real environment in the AR environment introduced in this system, when there is a problem in the actual building management, it can sufficiently be corrected without manual work, and it is also possible to prevent and prepare in advance.

Third, there is a high possibility of expanding the application range of the system and creating added value. The system in this study contains information and functions in the manager's perspective. However, it can also contain various information in the same way, expanding users to not only administrators but also students, professors, and visitors to campus. There is a high possibility that it will become useful by providing various data.

Future research will be on building and uploading additional databases of spatial data, such as electricity, facilities, and safety to the system. Currently, the system is built on four types of data: 1) construction data, 2) energy data, 3) entry and exit data, and 4) asset data. However, the fields of specialization for space management on campus manage more diverse and greater amounts of data. In addition, updates will be needed to manage the customized data required by each use, with the assistance of experts in work processing for space management.

Acknowledgement

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DECODING PARAMETRIC DESIGN DATA

Towards a Heterogeneous Design Search Space Remix

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Abstract. Designers or Non-Designers are not able to effectively access, view, search, discover, collect, reuse, remix and share parametric design data (PDD) for either professional or educational purposes. PDD here refers to the meta-data of 3D models generated by visual dataflow modelling software packages used in CAD/CAM industry. This ineffectiveness is a direct consequence of the deliberately proprietary nature of most PDD file formats and the restricted use within their respective desktop-based software environments. This paper presents an initial software prototype capable of automating the process of decoding a commonly used PDD file format and then re-encoding it with new set of metrics to facilitate multiple PDD searchability, comparability and interoperability, via an integrated web interface querying a design data repository. All PDDs are conceptualized as genealogies of numerical or geometric transformations and explicitly encoded with a graph-based data structure. The goal is to eventually learn from its own big data and begin to artificially generate novel PDDs heterogeneously.

Keywords. Design Decoder; Design Space Exploration; Parametric Design; Visual Analytics; Design Data.

1. Introduction

The ability to seamlessly access, search, compare, reuse, recombine and share multiple different parametric design data(PDD) could significantly facilitate the process of design search space exploration. PDD here refers to the meta-data of 3D models generated by visual dataflow modelling software packages used in CAD/-CAM industry. However, the diverse and deliberately proprietary set of parametric design software environments and file formats make these tasks difficult to achieve. This paper presents an initial prototype capable of automating the decoding and re-encoding process of multiple PDDs (figure 1) belonging to a commonly

used file format (Rhino3D's Grasshopper file), for the purposes of subsequent research development in recombining similar and diverse formats of PDD. In the decoding and re-encoding process, each PDD is identified or classified for ease of accessing and searching, decomposed or recomposed at different granularity for appropriate reusing and recombining, measured or evaluated for useful comparing and recommending, and stored or retrieved for real-time distributing and collecting. In other words, there are 3 main aspects addressed in the process, namely - searchability, comparability and re-combinability.

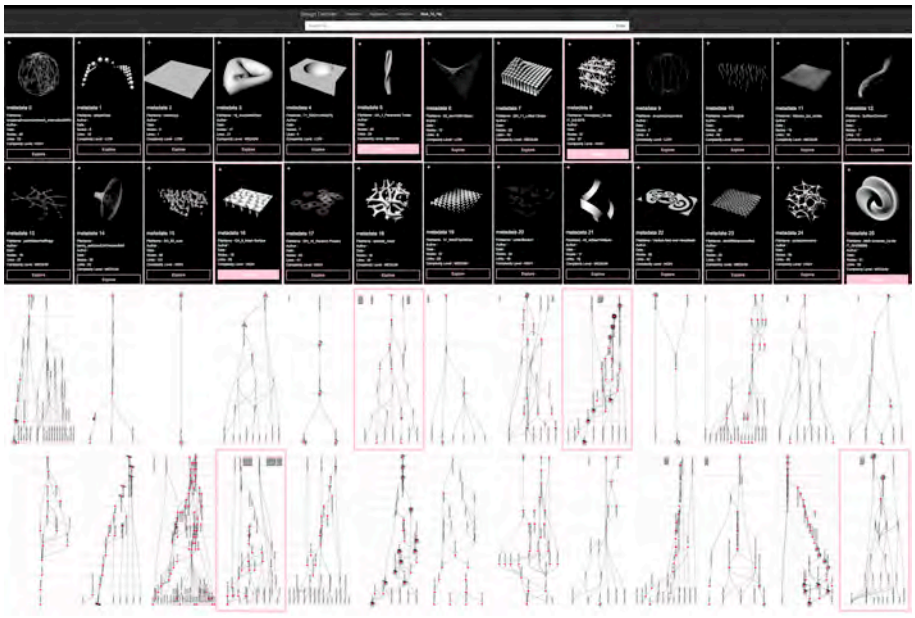


Figure 1. Web interface prototype showing a collection of parametric geometries and their corresponding 'DNA-like' genealogies structured and visualized with a new metric. These are generated from the decoded and re-encoded original Grasshopper files (.gh) in the database.

Firstly, to facilitate searching, classifications of design data are typically made using textual tags based on conceptual design associations, visual file formats or prescribed functional categories, which are manually entered by users and limited by the categories predetermined by the system (Dave & Gwyl 2012; Langenhan & Seifert 2012). Although these systems allow open online access by being platform agnostic and by displaying only non-PDD media; in doing so, the process of discovery ends immediately after the media search. This paper proposed a system that uses the PDD's decoded metadata for automated tagging, which in turn facilitate both the search and recommendation mechanisms with the use of text or image or 3d model selections as inputs (figure 2 & 3).

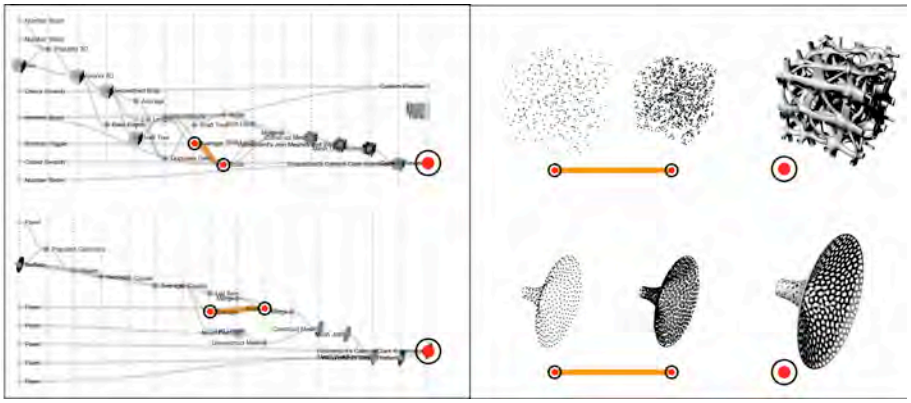


Figure 2. (Left): By accessing all the parametric models' genealogy ('DNA') within the database, the system is able to search for similar nodes and edges used in 2 or more parametric models. (Right): Corresponding nodes represented as individual instances of parametric geometries, where the edge denotes a similar sequence of 2 geometric operations (e.g. 'Average' and 'Scale').

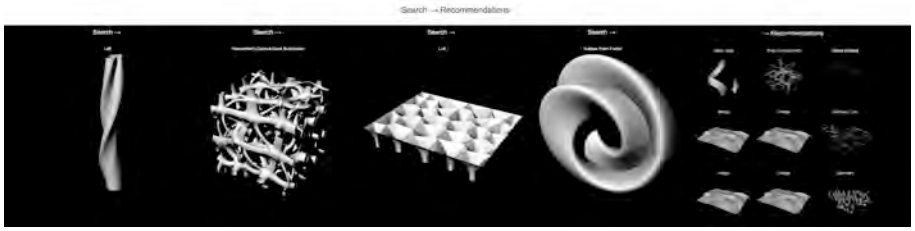


Figure 3. The user selection of one or more shapes causes the prototype to present the user with additional shapes based on design 'DNA' similarities (potential stylistic or functional similarities). The shape suggestions include the final shapes in the database and the partial shapes at various design stages. The goal is to inspire the user with shapes that have a high likeliness and thus helping the user to quickly iterate on design variations.

Secondly, on the issue of 3d digital design data comparison, the paper first differentiates the 2 classes of 3d digital models. Unlike the problem faced in computer vision or computer graphics, whereby the aim is to optimally recognize and compare different 3d digital models; the 3d digital design models concerned here are those that have been generated using parametric design software, whereby a corresponding parametric metadata file (for example, .gh or .ghx) is available for further analysis. The measure of similarity here is at the meta level rather than being necessarily outwardly identical (e.g. genetic composition versus final appearance). Thus, it can be argued that the comparative approach proposed in this paper is using the similarity in the rules of shape transformation (shape grammar) rather than that of the final transformed shape itself (Stiny & Mitchell 1978). Specifically, it is not the geometric topology of the 3d mesh but the topology of its genealogical network (Standfest 2014). Such a derivative approach would have been difficult in the past without the conveniently extractable network of shape rules embedded

in current PDD. The unique feature of a parametric computer-aided design environment is the explicit records of previous design states prior to generating the final parametric model. Attempts have been made to analyse and visualize these different design model states to provide alternative design moves during design space exploration by using a backtracking technique, implemented in the form of a plug-in to an existing parametric software environment (Sanchez and Erhan 2014). In this paper, all PDDs are conceptualized as genealogies of numerical/geometric transformations and explicitly encoded with a "DNA-like" or graph-based data structure (figure 4). More critically, the system uses this conceptual framework of genealogies to generates a multiplicity of new PDDs (i.e. new sub-graphs, sub-genealogies and sub-parametric models) from a single PDD, thus exposing the inherent design histories of each PDD for further reuse and remix (figure 5). Without being embedded within the Grasshopper host environment, the system directly parses any .gh files for decoding and re-encoding before storing them in a separate database. Therefore, once the PDD are re-encoded with this standardised new metrics and topological structure, the system is able to consistently measure, compare and retrieve multiple PDDs, by strategically incorporating a number of graph theory techniques, e.g. subgraph isomorphism (Weber et al. 2011).

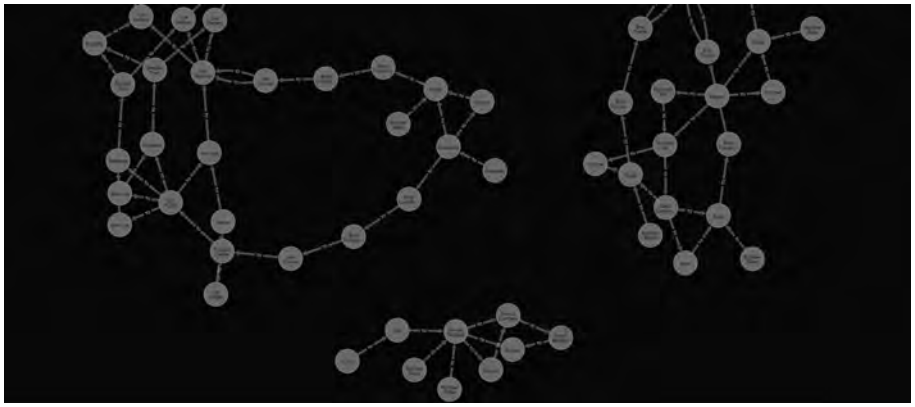


Figure 4. Snapshot view of the graph-based data structure of each PDD.

Thirdly is the issue of recombination for the purposes of expanding the design search space. Design space inherent to parametric design models consists of 3 different types, namely, implicit, explicit and hysteresis (Wood & Gün 2010). All 3 design spaces differ in their extent of varying the set of available numerical parameters, but share the same topological graph encoded in the original PDD. However, this paper proposes a system capable of remixing multiple graphs (original or new PDDs) and sub-graphs (derivative PDDs), which will in turn significantly exceed (both quantitatively and qualitatively) the original PDD's implicit design space. Thus, shifting from a predominantly inward-looking and linear design search solution to one that encourages and facilitates an outward-looking and lateral form of design search remixing. This paper proposes a recombination approach based on graph grammar, whereby the rewriting of PDD sub-graphs from different ge-

nealogical origins would generate new graphs (figure 6) and new parametric design models (Ehrig et al. 1973). Similar topological techniques using graph rewriting or recombining can also be found in the discourse of Case-based design, such as one which recombines rectilinear floor plans in a highly geometrically restrained manner (Dave et al. 1994).

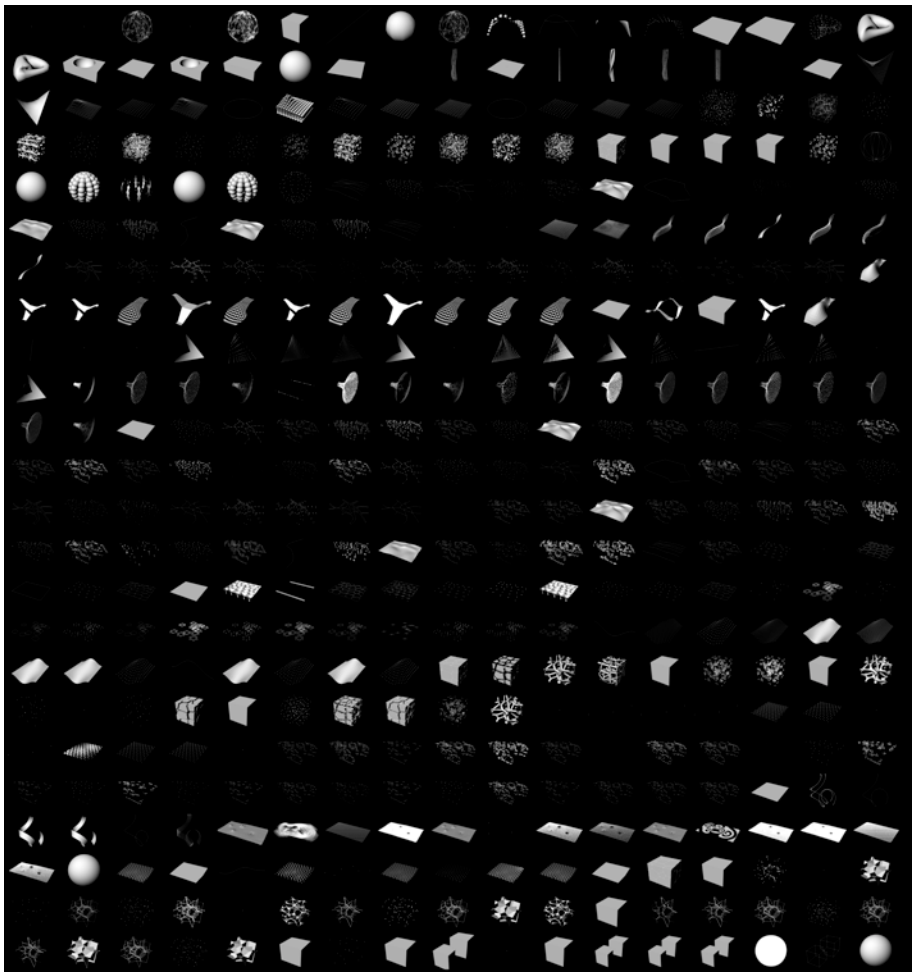


Figure 5. Sampled view of the database storing and auto-generating 3d models from the entire set of graphs and sub-graphs derived from the PDD files. An initial small sampling of 26 GH files could easily generate 420 new GH files based on the explicit design space alone.

2. Methods

The first stage of the research is to choose an appropriate parametric design data (PDD) file format for decoding and re-encoding. Among the various available PDD, Rhino3D's Grasshopper(GH) parametric design software is chosen because

of its vibrant and growing user base from both academia and practice, its strong and reliable technical support from the core software development team and its thriving open-source plug-in/libraries development contribution worldwide. There are 2 types of GH files in use, namely the '.ghx' file type and the more commonly used '.gh' file type, the former is an xml-based format readable by a standard text editor, while the latter can only be accessed via the GH graphical editor within the Rhino modeling interface itself. The obvious choice is to simply parse and read the tags embedded within the more standardized xml/ghx file, however, it soon become clear that the ghx file alone is an incomplete description of the meta-data when not accessed and executed by the GH runtime engine within Rhino. The decision is to then parse the more complete and commonly used '.gh' file instead, by first automating the external execution of the GH engine on the.gh files.

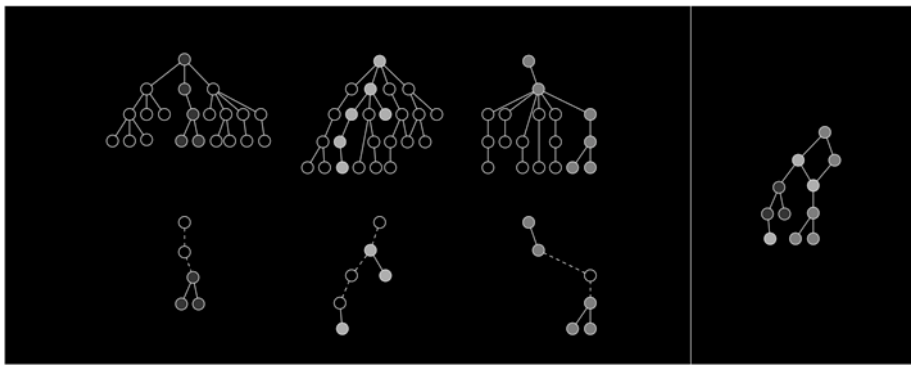


Figure 6. (Top Left): Selecting 3 instances (shaded circles) of 3 different PDD genealogies (unshaded). (Bottom Left): Partial selection of their respective sub-graphs. (Right): Recombining the sub-graphs to generate a new heterogeneous PDD graph.

A custom set of Python codes (alongside RhinoCommon and Grasshopper SDK) is developed to batch process the '.gh' files, in order to automatically load, parse, extract, render, reformat and store all the nodes/links information in a database. Specified settings for rendering(.png) and 3D mesh reconstruction(.json) of all the geometry containing GH nodes are also indirectly generated from the original metadata for the purposes of visualization on the web-based interface (figure 7). Due to a lack of an existing centralized Grasshopper file repository online, a web-scraper is written to scrap a sampling of GH files from the Grasshopper3D website itself. A graph database is used to store the extracted PDD's metadata as a topological entity (graph). An initial search and comparison metric is proposed using techniques found in graph theory, as well as, other intuitive parametric design related properties. For instance, two or more entities can be topological compared based on isomorphism, sub-graph isomorphism, vertex similarity, edge similarity, graph distances, maximum independent vertex set...etc. Each entity also has its own GH specific statistical property encoded, such as total genealogical levels, externals add-ons dependencies, node quantities, edge quantities, geometrical and numerical node ratio...etc.

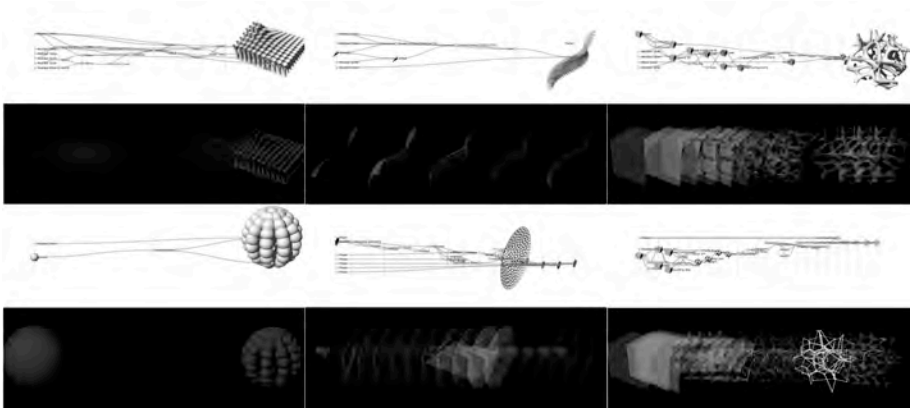


Figure 7. Automatically rendered 2D images and reconstructed 3D models ordered along the genealogical x-axis. Interface includes synchronized panels' highlighting with cursor interaction.

Another custom set of codes is developed and written in JavaScript/HTML/CSS to visualize the data on the browser which allows user to query data from the backend database in real-time. The 2D SVG generation uses D3.js library, the 3D mesh generation uses Three.js library, the UI uses Bootstrap framework (alongside its dependencies jQuery) and the database query uses Neo4j's Cypher language. The frontend interface consists of the following functionalities: (a) Discovery component, where user could view and select from a dataset of recent or trending PDDs, (b) Recommendation component, where a similar set of PDD is being queried and presented to the user based on the currently selected PDD, (c) Management component, where user could make a personal collection of the selected PDD, (d) Remix component, where user could combine any PDD within his collection to generate new PDD both offline and online (still under development as of this writing). In (a), each PDD is represented with a thumbnail 3D rendering of its last Grasshopper geometric evolution and user has the option to interactively expand or explore all the meta-data of the PDD. The decoded meta-data includes a re-ordered graph connectivity diagram spatially plotted according to its geometric evolution sequence (from left to right), and accompanied by a corresponding image-based sequence (figure 8). This re-ordering is a hybrid flow diagram that rebuilds a graph based on a set of nodes and links to automatically positions them both horizontally and vertically with minimal links graphical overlaps using an iterative relaxation computing process. Within this expanded design data view, the user has an option to visualize a time-based animation that illustrates the sequences of node placement when the author of the original '.gh' file first created the file. Similarly, a set of 3 interactive statistical bar charts (figure 9) can be triggered to visualize the categorical or sub-categorical or primary nodes used in each '.gh' file.

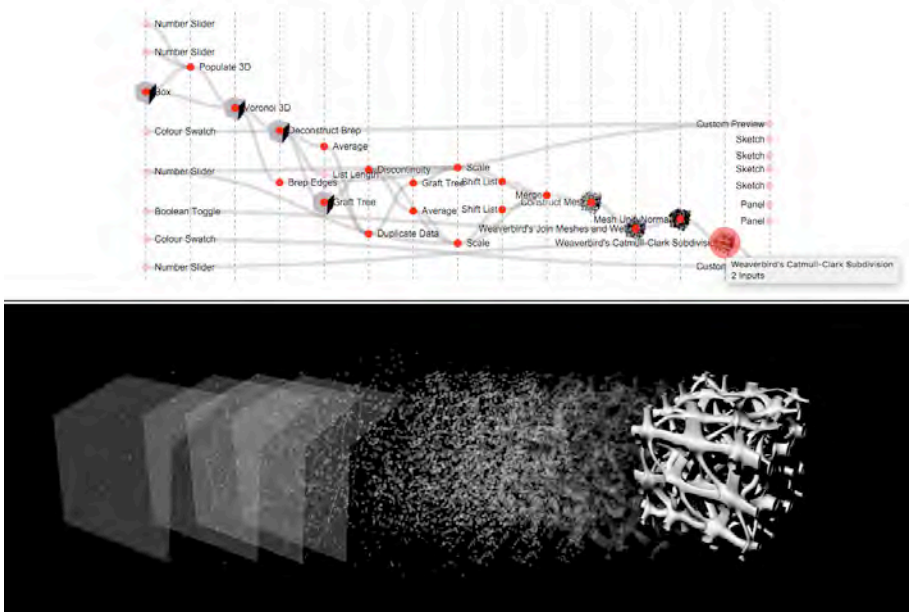


Figure 8. (Top): Using iterative relaxation to reorder the original GH layout based on a consistent layout metric. Automatic color coding with red circles representing geometric nodes and pink circles representing numerical or string nodes. Nodes sequences extracted from the .gh metadata can be animated with the colored circles to demonstrate their actual sequential placement when first created.

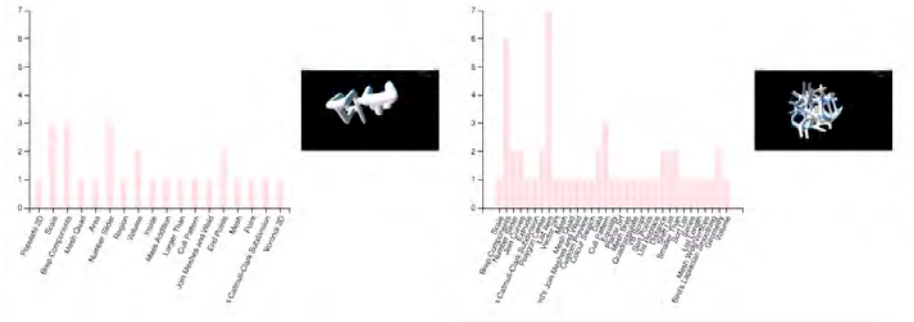


Figure 9. Statistics of each PDD being interactively visualized.

In addition to this expanded model view of each design data, the interface also presents an overview summary of the top trending nodes and node sequences used by all the individual PDD stored in the database, by automatically sorting these parameters for the user's reference. In (b), the list of recommendation is generated based on the similarity shared among the design data using criteria, e.g. similar nodes used, similar sequences of nodes and level of complexity. A query would be made to the graph database and the results would be returned immediately in a

visual manner for user's consideration. This same recommendation system is also triggered whenever a user hover-over any nodes on the flow diagram (under the expanded model view). In (d), the user could either download the corresponding '.gh' file in order to work on them offline or work directly on the PDD online (still under development as of this writing).

3. Results

The current prototype has successfully decoded and re-encoded an important design data type ('.gh') – one that is commonly used in contemporary architectural design workflow for parametric modeling. It has also managed to create an interface and parametric design data repository that allows user to effectively discover, search, collect design data in a quick and visual-friendly manner, while being aided by a recommendation system. However, the implementation of the real-time multiple PDDs recombination is yet to be completed until the forthcoming months.

4. Conclusions

Since this is an initial prototype, the subsequent stages for the research is to complete the design and automation aspects of PDD recombination before the decoding of other PDD file formats that are used in industry (e.g. Generative Components...etc.). As part of a larger research agenda, the goal is to eventually learn from its own repository's big data and begin to artificially generate novel PDD by varying the graph's compositional patterns, thus further expanding the design search space of the users. Thus, this research could potentially be conceived both as an educational tool in providing creative play and interactive learning of PDD in general, and as a professional tool in facilitating effective PDD retrieval and generation given a time-constrained design environment.

Acknowledgements

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UNDERSTANDING COGNITIVE OVERLOAD IN GENERATIVE DESIGN

An Epistemic Action Analysis

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Abstract. Choice overload is experienced when designers use generative systems to explore a large number of alternatives. In an experiment, we studied the epistemic actions designers perform to reduce their cognitive load caused by possible choice overload during design exploration. The participants were asked to select alternatives among a large set of solutions in a simulated design environment. For data encoding, we adapted an epistemic action analysis method to understand which actions occurs in what phase of design. Most epistemic actions are observed during criteria applying phase. The most frequent actions were 'clustering and grouping' and 'talking and gestures to guide attention'. Ultimately our goal is to answer if a system can alleviate the possible cognitive overload when working with a large number of alternatives, if so how they would look when implemented.

Keywords. Generative design; parametric modeling; cognitive overload; selection; epistemic actions.

1. Introduction and Motivation

In the presented study, we aim to explore the role of epistemic actions that designers perform to alleviate the cognitive overload that may occur when generating and exploring a large number of design alternatives under a set of (design) choices. An epistemic action's primary goal is improving cognition by reducing the memory, the number of steps, or the probability of error in mental computation (Kirsh & Maglio 1994). By a 'design choice' here, we refer to the salient decisions a designer can possibly make in the course of design that can be observed and evaluated. In parametric design, for example, value assignment to a parameter from an arbitrary range of possible values, deciding to add or subtract a design feature, or selecting a set of deriving parameters for creating solutions are design choices.

A design alternative, consequently, is a generated solution using a particular set of design choices. We hypothesize that the possibility of a large number of design alternatives and design choices compounded with the lack of tool support for working with them can cause designers to face with cognitive overload problems. For the purpose of this study we define cognitive overload as the demand made on the cognitive system (Fan & Lei 2006) that exceeds the capacity and the capabilities of the human cognition and the available cognitive artifacts. For example, cognitive overload problem may manifest itself when designers are simultaneously creating and controlling design models that are driven by an arbitrary range of possible parameters, which in turn can result with a rapidly growing solutions.

Lack of tools to support epistemic actions can impede determining the design criteria, creating and evaluating design alternatives, and managing them. The systems for editing a single model (Terry et al. 2004), by description, is not intended for creating multiple alternatives. We contend that the choice overload is expected and normal without a proper and direct system support to navigate through possible choices and alternatives, and to assess their outcome. Finding about the epistemic actions can help us to create design systems where choices can be tested rapidly in large numbers by the tools for supporting such actions. But what are these epistemic actions, when do they appear in the design process, what are the frequencies, and what does trigger them? More importantly, if and how they can be translated into tool features.

As a first step to seek answers to such questions, we conducted an experiment to explore the epistemic actions that may take place when working with a large number of alternatives. The epistemic actions performed in an existing system can be relatively easy to observe. For example, in parametric design, using descriptive names for solutions to group them is a memory-saving action; organizing the layout of a propagation-based graph for reducing later search time of particular parameters is a time-saving action; and testing multiple values for parameters before committing to a value can reduce probability in error in the later stages. However, we have yet to have a system to support working with a large set of alternatives created using a large set of choices. In the study we asked designers to work in a simulated design setting where they are required to identify plausible design solutions among a given large number of possible designs. Along with the basic criteria and parameter set given, they are encouraged to introduce their own criteria if and when needed. We attempted to address the reasons as to why, where, and when cognitive overload problems may occur when working with alternatives, and what actions can reduce such problems.

2. Background: Choice Overload Affecting Decision-making

The choice overload hypothesis has been under evaluation over couple of decades. The hypothesis states that an increase in the number of options to choose from may lead to adverse consequences such as a decrease in the motivation to choose or the satisfaction with the finally chosen option. However, there are contradicting findings in the literature as well. The meta-analysis of the research on this topic by Scheibehenne, Greifeneder & Todd (2010) and later by Chernev, Böckenholt, Goodman (2015) questioned when large choices can improve the output

of the task and when they can create bottlenecks in the process of choice. Iyengar & Lepper (2000) studies the decision complexity caused, at least partially, by the (large) number of available decision alternatives. Most research is conducted in the marketing domains where product choices are presented to the consumers, and possibly not giving enough preparation or assisting tools to manage choosing among the alternatives. They also limit the number of choices to about maximum 30 options so that the decision maker can complete the given task in a strictly defined settings. In design, however we have a different scenario where designers are the ones who define the goals, solutions, and tools to be used in completing the design task, which is usually open-ended and more rewarding due to their creative nature. Hence, the result of choice overload can be a relative phenomena and can be taken differently from one domain to another, and from one task to another.

In data analysis domain, Woods et al. (2002) identified three characteristics of information overload on cognition: (a) there is too much data in the workspace, creating clutter; (b) the abundance of data creates a workload bottleneck because there is too much information to sort through the in the available time; (c) finding the significance of the data is a challenge because at the outset it is hard to know where to look. Following can reduce the cognitive overload: (a) reducing the amount of data units displayed; (b) automation or cooperation with other cognitive agents; and (c) representing the data in a way so significant data emerges.

The search to find a solution take place in a problem space (Simon 1955) that can be expanded to include user's knowledge combined with any available external resources (Ashcraft & Klein 2010) in both the physical and informational states (Kirsh & Maglio 1994). What creates significance for a piece of data in a problem space includes: (a) other related data; (b) how the set of related data can vary with larger context; (c) the goals and expectations of the observer; (d) the state of the problem-solving process and stance of others.

Woods, Patterson & Roth (2002) characterizes three ideas in the nature of data overload faced by our cognitive systems: (a) data overload is difficult because of the context sensitivity problem-meaning lies not in data, but in relationships of data to interests and expectations (b) new waves of technology exacerbate data overload when they ignore or try to finesse context sensitivity; (c) the mechanisms of human perception and cognition that enable people to focus on the relevant subset of the available data despite the fact that what is interesting depends on context. They identified particular constraints that must be met for all potential solutions, particularly the idea of organization preceding selection. They describe a data availability paradox, that as the technology easily increases the data available, the human ability to interpret the data has not kept up. While beneficial in some ways, it is also problematic in how we must have more and more effortful search for finding something meaningful and informative that meets our goals and tasks. Scheibehenne et al. (2002) states that a large assortment of choice make exhaustive search undesirable in terms of time and effort, which could contribute to fears of a less than optimal choice (such as second best). This wide availability of data can be key to our success, but only if we are not made vulnerable by it (Woods et al. 2002).

3. Method

In a simulated task environment, we observed the designers' behaviour when they were asked to work with a large number of generated design solutions. Note that, the data collected in this study aimed to answer other relevant questions in addition to the ones concerned here. In this study, we mainly used the video recordings, since they directly expose the designers' moves and their comments. When needed, we turned to the questionnaires and in-depth interviews. We applied a mixed-method approach combining qualitative research analysis with supporting visual analysis and quantitative techniques.

4. Participants and Task

Ten designers volunteered to participate in this study, one of which we used as the pilot case to develop a protocol and to test the interrater reliability. For our purpose and an initial experiment we found this acceptable. We expected to recruit architectural designers with experience in parametric CAD for design exploration. However, due to lack of availability for such participants, we resorted to recruiting for a partial experience match. Four participants had experience in architectural design and parametric CAD. Five participants had experience in other design disciplines (graphic design and industrial design). They all use of various computational tools in their design. One of the participants had experience in real estate and graphics design.

Participants were given 1000+ building design alternatives generated using 27 independent parameters (c.f. Erhan et al. 2014 and Wang 2015). We chose visually diverse alternatives to be as stimulating as possible (figure 1). They were asked to go through the given alternatives and select the possible solutions using their own methods and strategies. They were encouraged to propose additional requirements for the building design. The task was deliberately open to interpretation to ensure that they can make their own choices.

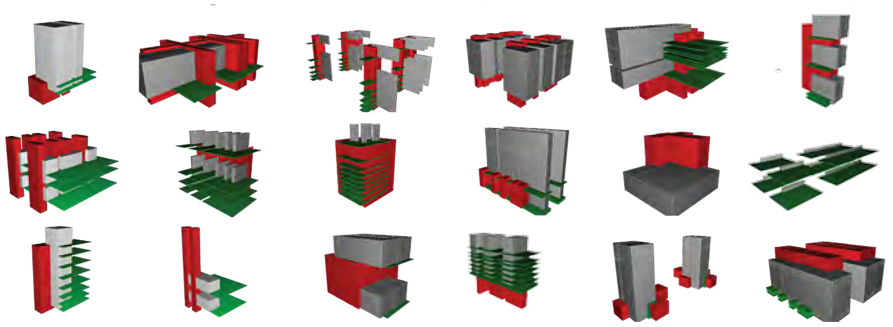


Figure 1. Sample design alternatives from the set used in the study.

The large number of alternatives and openness ensures the participants are overloaded with choices. In real life, designers may add information to turn more unknowns into knowns. However, more or less parts of the problems always remain to be discovered. Also, designers may be overloaded with a different number of

choices, influenced by the task environment, tools, and of course individual differences. In this study, participants are limited to using alternatives printed on index cards, pen and paper, and whiteboards. Participants were told to expect the average task time to be 1.5 to 2 hours, but they could spend as much or as little time as they wished to. The actual time spent on this task by 10 participants ranged between 0.5 to 3 hours.

5. Procedure

The study was conducted in a small room with two whiteboards on adjacent walls (figure 2-Left). Four cameras were used to record participants' actions: two recorders (red stars) to capture the two white boards; one (GoPro1) to capture an overview of the table; one (GoPro2) mounted on the forehead to get a general proximity of the participant's attention. One observer and one note taker were sitting in the corners of the room to be as nonintrusive as possible. The table was angled to give ease of access to both white boards. Figure 2-Right shows time-lapsed view from the overhead camera, with five minutes of footage overlaid on a single image frame.

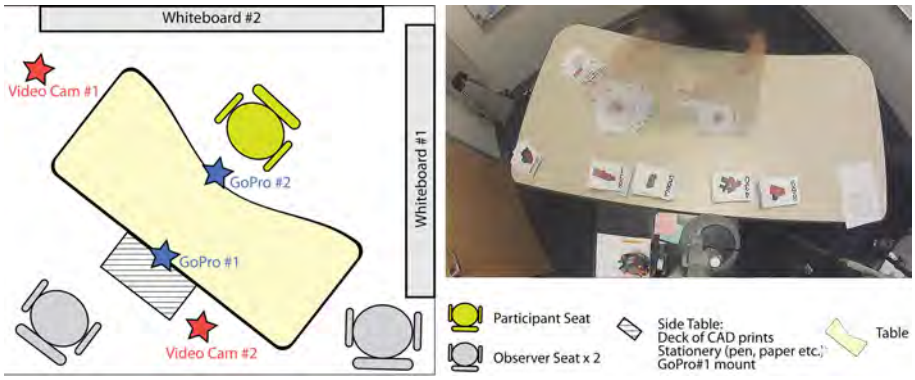


Figure 2. (Left) Observational Study Room Setup, (Right) Time-lapsed view from the head strapped camera over a period of 4 minutes.

6. Analysis Methods and Process

We adapted the epistemic actions analysis developed by Esteves et al. (2015) that focuses on a set of epistemic actions identified through an extensive literature review, and measures different epistemic actions during problem-solving tasks. While the method designed for 'tangible interaction', its generality is based on problem solving and hence is suitable also for analyzing the design tasks. Out of the proposed 20 epistemic actions, we selected 18 after our first pass on the videos (Table 1). Previously, Wang (2015) identified four different phases by analyzing the same videos. She found that the participants commonly follow the same cycle consistent with design literature for describing design exploration (Maher & Poon 1996; Brown 2009). Evidence from her study confirms that designing with generated alternatives follows the same cyclic pattern as general design exploration process (figure 3). Below are the definitions of the phases (Wang 2015).

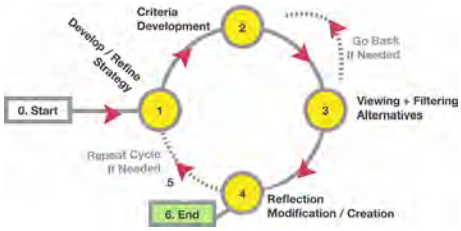


Figure 3. Observed cycle for design exploration with a large number of alternatives.

Table 1. The epistemic actions and possible interpretation.

	Epistemic Action	**Example interpretation**
1	Clustering or grouping artifacts together	Adding a car or cards to pile
2	Spatial arrangement of artifacts in relation to one another, the task environment or the user(s)	Creating piles of cards
3	Rearrange a representation	Shift piles or cards around
4	Manipulation of an artifact	Moving, rotating a card, taking or dividing handfuls from a stack
5	Tag or annotate an artifact	Write on a card
6	Using the body to externalize an internal process	Talking to oneself
7	Annotate	Write on something not on a card, e.g. sticky, paper, whiteboard
8	Bodily marking an artifact	Keeping finger on a card, keeping a card close to body
9	Build a model or external representation	Explicitly establish a criterion
10	Bimanual use of two artifacts, two representations, or an artifact and a representation	Holding or comparing two cards in hand
11	Divide workspace into several stations in which only a subset of actions is afforded	Interpreted same as 12
12	Place artifact in a contrasting environment	Moving piles or cards into a separate distinct area e.g. move from table to whiteboard
13	Compare an artifact with a possible destination or other artifacts	Interpreted same as 10
14	Talking or gesturing to guide and direct attention	Talking or gesturing to researchers
15	Use of an artifact or tool to physically constraint the user, or the user of other artifacts and tools	Using tools to perform an action or help decision making, e.g. use a ruler to estimate scale
16	Clear and clean clutter	Remove discard piles or large quantities of cards from workspace
17	Shuffle artifacts	By description
18	Test the state or response of a system, model	Review or check brief sheet

Criteria (re)Building: Define a criterion to decide how to treat a given set of alternatives including when a criterion is replaced with a different criterion, rearranging criteria, eliminating a criterion or redefining its meanings.

Criteria (re)Applying: Reconsider the qualities of an alternative against one of the chosen criterion.

Criteria Testing: After introducing a criterion, test the first round of selections' acceptability. We observed multiple instances where a criterion tested and

tentatively accepted until if it is no more relevant.

Reflection and Resetting: Take pauses to reflect on the process to explain what have done so far, what would be the next move. The designers may continue or may simply reject the previous moves and restart with a new strategy.

Two encoders separately analyzed the pilot case following the initial protocol established. The interrater reliability (89% Cronbach's Alpha) was achieved in 10 minute intervals by looking for 18 epistemic actions in the four predefined categories. The actions were identified by both visual descriptions recorded (Table 1) as well as the verbal descriptions of the participants at the time when the action is observed. The pilot study revealed that not every action had a corresponding category, since some actions failed to meet the predefined categories. We added two new categories: (a) **task evaluation**, which refers to the actions that defines the objectives of the new task, and typically prior to building any particular criteria; and (b) **task organization** that includes actions observed when the participants already set their objective but before performing actions outside of criteria building and applying.

The data recorded includes the time when the action is observed, the duration of the action, the category of the phase in which the action is observed, and the researchers note on that particular action. We analyzed the data after combining the findings from each encoder and normalizing the task time.

7. Findings

We observed that most frequent epistemic actions are 'clustering and grouping', 'using body to externalize an internal process', and 'talking or gesture to guide attention' (figure 4). Although, higher frequency does not necessarily mean that these are the most decisive moves, they definitely help managing the cognitive load. The last two reveals 'thinking' about the actions taken or to be taken. The least observed actions were 'placing artifact in a contrasting environment' and 'building a model or external representation'. 'Tagging and annotating artifacts' and 'dividing workspace into stations' are rare actions.

Criteria Building is the most dominant phase at the start of the task, which gradually decreases (figure 5). Six participants built criteria at or near the beginning and once again towards the end (figure 6). Building of criteria at the start could be interpreted as formulation of a model for the selection process to follow. Criteria building at the end could be interpreted as formulation or revisiting of discarded items as "bad examples", which is the analysis of non-candidate solutions as a strategy to manage data overload. The participants may have employed this strategy towards the end as a means to lighten their cognitive load and organize their thoughts for explanation.

Reflection is also seen throughout, though most commonly seems to occur after spurts of *Criteria Applying*. This may be a self-evaluation or evaluation of the just performed action in how much or how in line it is to expectations. *Task Evaluation* is expectedly at the start of the task, when participants are familiarizing themselves with the expectations, environment, task etc. *Task Organization* is quite spread out, some notably occurring after criteria applying. This may be due to simple

neatening and straightening up of item stacks or may be reorientations or refreshing of perspective, another effective constraint against data overload as pointed out by Woods et al. (2002).

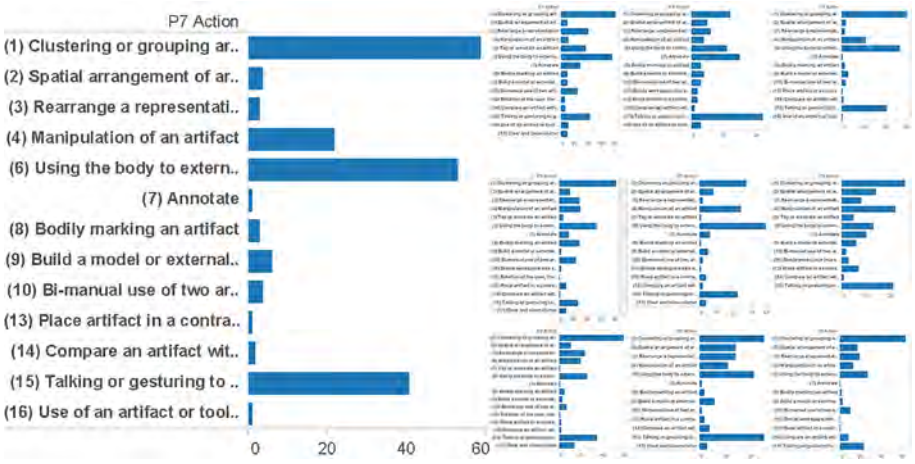


Figure 4. Action frequency observed.

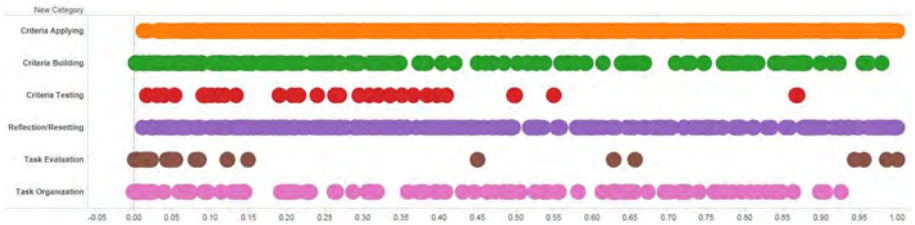


Figure 5. Epistemic actions observed during each phase distributed over normalized task time.

In *Criteria Applying*, the most frequent actions are 'clustering or grouping artifacts together' and 'using body to externalize an internal process'. In 'Reflection' phase, however, particularly 'talking and gesturing' appear more than the others. This is consistent with the literature as it requires less effort than other actions in reflecting in the process. We wonder, however, if the participants were asked to describe their reflection on their actions through other means but talking, how would they explain their choices.

Eight participants reported having difficulty narrowing down alternatives. Some participants referred to the task as more focused on grouping rather than elimination. Initial criteria development was challenging due to lack of constraints and knowledge about the generated sets. Participants made their own assumptions of the situation and define their own rules and understanding of the set. There are difficulties in deciding about each individual alternative. Participants reported "sitting on the fence" for many of the alternatives and "questioning about the se-

lection, [...] if it's an error, yea, definitely an error". Also as a concept matured, adding or removing alternatives from a group of selected criteria becomes harder due to the fear of having too many elements confusing their intent: "I want to make my elements of design as clean as possible, not too much junk, [...] my interest is in this kind of geometry, now is the new addition going to help to clarify it, or is it going to be two different kind of designs?" Three participants mentioned a desire to go through all 1000 alternatives to avoid "missing out on something interesting." One participant that finished viewing all 1000 alternatives in the session.

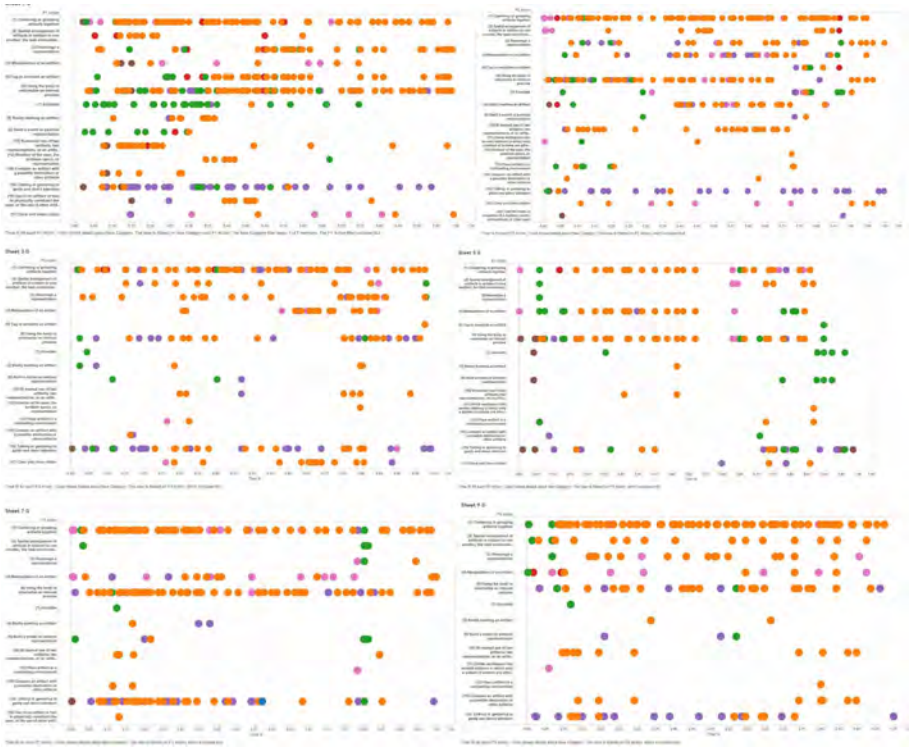


Figure 6. Epistemic actions performed during each predefined phase (use figure 5 as legend).

8. Conclusions and Discussion

We examined the epistemic actions designers perform to manage their choice overload that may be experienced when working with a large number of alternatives. We borrowed a list of epistemic actions from Esteves et al. (2015) and design phases from Wang (2015) in encoding the data. We identified the epistemic actions, when they take place, and how often the designers rely on them. The findings show that criteria applying is the most intense phase in design with possibly clustering and grouping is the most frequent action observed. These actions should be treated differently in designing a new system. While participants were encouraged

to describe their actions, the encoders might confused them with the 'talk and reflect' epistemic action. Identifying its effect on the action count and categorization would be difficult; however, their talk (aloud) might have helped unintentionally in making the selection of alternatives. This may be a discussion point in further studies.

While computational tools have potential to generate a large space of solutions, they provide almost no direct features for the epistemic actions in the natural workflow of design. We can integrate design generation and exploration by eliminating the extra task layers imposed by most systems. The system features for this can be revealed by observing how designers act when they make design choices. To alleviate the hypothesized cognitive overload problem, what are the functional and structural system properties? How can we identify these properties and how could they be implemented? We leave the discussion on these questions to another paper.

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ALGORITHMIC-BASED ANALYSIS

Design and Analysis in a Multi Back-end Generative Tool

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Abstract. Estimating a building's performance is part of the engineering and architecture discipline. Nowadays, this estimation is done using analysis tools. In many cases, these analysis tools require specialized building models that are simplifications of the actual models. Unfortunately, the adaptations that need to be done to an existing model are tiresome and make the architect less willing to evaluate variations of the building design. Moreover, in the case of buildings with complex shapes, the analyses tend to be less reliable. These problems also occur when algorithmic approaches are used to generate the building design, as the algorithmic script needs to be adapted to satisfy the requirements of the analysis tool, or the manual adaptation of the generated model needs to be repeated each time the script is executed. To solve these issues we propose Algorithmic-Based Analysis. This is a Generative Design method that, utilizing a single algorithmic-based representation of a building, can generate not only the traditional CAD or BIM model, but also specialized models for use in different kinds of analysis.

Keywords. Generative Design; Building Performance; Analysis; Performance-based Design; Algorithmic-Based Analysis.

1. Introduction

3D modeling applications changed the design paradigm, altering the way architects approach building design. This shift opened the door for yet another technological leap: the development of parametric tools driven by algorithmic processes. Using an algorithmic approach, instead of creating a model of the intended design, architects can implement an algorithmic description. This description, when executed by a computer, creates the actual design and, when appropriate, variations of that

design. This allows architects to not only achieve new shapes (Yusuf 2012), but also to more rapidly change those shapes (Lopes & Leitão 2011). This approach enables faster exploration of variations of the envisioned design and promotes a more informed search for the optimal variations. As can be expected, the pursuit of higher levels of complexity in buildings' geometry has challenged fabrication and construction methods (Kolarevic 2011). This has made building designs less predictable from, e.g., the thermal, lighting, and acoustics points of view. As a result, it became critical to have an evaluation of buildings' performance.

Analyzing a building's performance has long been part of the engineering discipline. In the past, these analyses have been done through tiresome and error-prone manual calculations. These calculations have recently been implemented in specialized computational tools that perform them using data extracted directly from a 3D model of the building, as well as from information regarding the building's location and materials. The use of these tools has greatly reduced the amount of time needed to perform analysis, as well as the rate of human error.

Analysis tools require a geometric model of the building that, unfortunately, is frequently different from the one produced in the 3D modeling tool, thus requiring a translation process (Aghemo et al. 2013). Usually, this forces the analyst to do some preparation work before an analysis can be done, which becomes tiresome when buildings are generated using algorithmic approaches, as it needs to be repeated for each variation of the building. Given that the time and effort spent in the preparation for analysis are not negligible, performing repetitive analyses inhibits the designer's desire to perform more than just a few of them. This deterrence drastically reduces the potential of the algorithmic approach for finding the design that maximizes the desired building's performance.

In order to solve this conflict between the capability to algorithmically generate a large number of design variations and the effort needed to prepare each variation for analysis, we propose a set of modeling operations that can not only generate the usual 3D model, but also generate specialized versions that are pre-prepared for analysis. Moreover, to deal with the fact that different analyses might require different representations of a building, we propose using an implementation of the modeling operations that is dependent on the modeling goal. This means that a 3D model that is algorithmically generated for, e.g., rendering, employs different geometric objects than the same model when generated for, e.g., daylight analysis.

In this paper, we present an implementation of this proposal, which we call Algorithmic-Based Analysis. We show its potential for bringing architecture closer to performance-based design, a process where the building is conceived with the aim of fulfilling performance requirements such as thermal loads, lighting or structural behavior.

1.1. ANALYSIS SOFTWARE

Nowadays there are many tools available for daylight, thermal, and energy analysis, most of which, require the digital model to be in a particular format. Changing a 3D model's format many times causes information loss, and, in some cases, the analysis tools cannot even deal with complex geometry (Moon et al. 2011), which

forces the user to remodel a simplified version of his creation.

Ideally, the modeling and the analysis tools should exchange data seamlessly. This is actually possible in some design programs that have analysis tools built into them. For example, Revit, a program that supports the BIM paradigm, provides structural, solar radiation, and thermal analysis. This avoids the need to rebuild the model or export it to other formats. Unfortunately, that is not the case for other important analysis tools, such as Radiance (Fritz & Macneill 2016) or DAYSIM (Reinhart 2016), for daylight analysis, and EnergyPlus or Ecotect, for energy simulation. Each of these programs requires a building modeled according to specific geometric requirements and exported in a particular format.

To overcome this problem, more integrated approaches began appearing in the market, for example, DIVA - Design Iterate Validate Adapt - (Niemasz 2016), a plug-in for Rhinoceros that incorporates the analysis provided by Energy Plus, Radiance, and DAYSIM. The main drawback of DIVA, however, is the amount of adaptation that it requires in the building's model so that it complies with the tool's requirements. This adaptation might require considerable efforts, and is, therefore, unsuitable for generative processes that can produce several different variations of a building. This issue will be further discussed in section "Comparing Approaches".

Despite these shortcomings, DIVA is currently integrated with Grasshopper (Davidson 2016), a Generative Design (GD) tool, allowing for the mechanization of the analysis process. However, this analysis process still requires the modeled building to follow the requirements of Grasshopper and DIVA. Furthermore, the time it takes to do even the simplest analysis makes the process unsuitable for the highly interactive nature of Grasshopper.

As is apparent with the DIVA-Grasshopper integration, the use of GD is not a solution that avoids the need to generate specialized building models for different kinds of analysis. Instead of forcing the designer to manually adapt his models, it now forces him to manually adapt the programs that generate the models. However, if we focus on portable GD (Lopes & Leitão 2011), an approach that allows the same program to generate equivalent models in different CAD/BIM tools, then it becomes possible to use the same modeling operations for different purposes, namely, analysis. Moreover, by implementing specialized analysis operations, that are taken into account by specific analysis tools and are ignored by other tools, we allow the same algorithmic description of a design to be used for advanced analysis without disrupting the model's other uses. We call this approach Algorithmic-Based Analysis.

2. Algorithmic-Based Analysis

In order to support Algorithmic-Based Analysis we first need portable GD. To this end, we used Rosetta (Lopes & Leitão 2011), a programming environment that supports scripts written in various programming languages, and which generates equivalent models in a series of CAD applications that are known as back-ends. Due to the recent integration of BIM back-ends in Rosetta (Feist et al. 2016), it also has operations available for modeling the parts of a BIM model. These oper-

ations include slabs, walls, columns, and beams, among others. Rosetta provides an abstraction layer that encompasses the common operations, such as shape constructors and transformations, amongst the back-ends. The abstraction layer is then translated into the requirements of each back-end. This means that the same script is interpreted differently by each one of them. Despite this fact, equivalent models are seamlessly produced in the various back-ends.

As explained before, analysis tools, such as Radiance and EnergyPlus, require a simplified version of the 3D model. To this end, we extended Rosetta with additional specialized back-ends with the purpose of generating models for analysis. Hence, from the same script that produces a detailed model in a CAD or BIM application, Rosetta's analysis back-ends generate the specialized version of the model that is needed for the desired analysis. For instance, in the case of the back-end tool for Radiance and DAYSIM, slabs, beams, and columns are interpreted as mere planes and surfaces. This information adaptation will also reduce the computational resources required to perform the analysis, and therefore reduce the time that it takes to run the analysis.

In the next section, we describe the Algorithmic-Based Analysis workflow in the context of Rosetta, and we compare this workflow with the well-known DIVA-based workflow. After this section, we present an evaluation of the process in a case-study.

2.1. ANALYSIS WORKFLOW

Before using an analysis tool, a designer will usually have already modeled their design as a generic 3D model. These models frequently have far more detail than is required for the analysis. This generic model would be a good starting point if the designer's analysis tool could use it, but this is not always the case. Sometimes the analysis tool requires the designer to change the model, e.g., to simplify it. In other cases, the designer must rebuild the model completely. As an example, figure 1 (left) synthesizes the information exchange needed to perform an analysis using DIVA and Radiance. In this exchange, the user begins by building a 3D model in Rhino. After some manual changes to the geometry (1) the model is exported to Radiance and evaluated. It then returns the results back to Rhino where the user can see them (2).

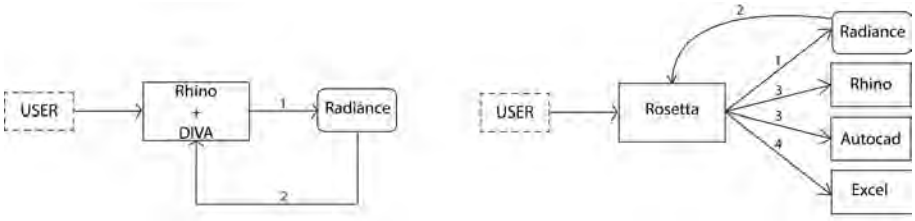


Figure 1. The DIVA workflow (left) and the Rosetta workflow (right).

When using Rosetta's analysis back-end, the geometry of the model is generated in the way required by the analysis tool. The practical result is that, despite the user's script being the same, the model given to the analysis back-end is independent and different from the model produced in the visualization back-end. The model generated by Rosetta contains all required elements and simplifications that the user would otherwise have to do manually. Figure 1 (right) illustrates this process for the Radiance tool. The user scripts his design in Rosetta, with no concerns regarding the analysis tools requirements. (1) Rosetta then sends only the necessary information to Radiance for the analysis. After the analysis is concluded, (2) the results are retrieved and (3) displayed in the 3D modeling backend, e.g., Rhino or AutoCAD, or (4) they are exported for further processing, for example, in Excel.

We call this method Algorithmic-Based Analysis because the level of detail or features of the algorithmically generated building are produced according to the analysis needs. This approach makes it easier for the architect to introduce changes to the design script, which are then automatically translated according to the analysis tools' requirements. Therefore, as change becomes effortless, the architect is more willing to try variations of his model. Moreover, possible misinterpretations and information loss are eliminated. This is due to the fact that the model geometry, that is fed to the analysis software, is generated according to the analysis software's requirements. This makes the analysis results more trustworthy.

3. Evaluation

To evaluate our approach, we selected two distinct case studies: Astana National Library, from Bjarke Ingels Group, and Absolute Towers from MAD Architects. Astana's façade is covered with triangular panels with different openings defined according to the building's light exposition. The Absolute Towers feature smooth, unbroken balconies all around each floor. In addition, as the buildings rise, the slabs rotate, offering them a curvaceous figure. A perspective of the library's structure can be seen in figure 2 on the left, while a detail from one of the towers is shown on the right.

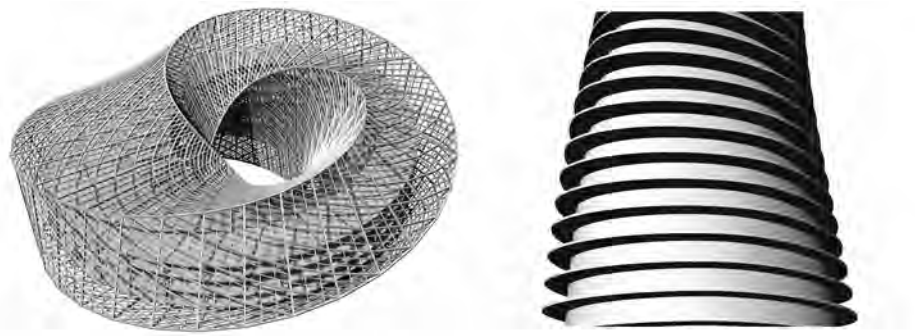


Figure 2. Astana National Library's Structure (left) and Absolute World Towers' detail (right).

Both models were built using Rosetta making it possible to change several aspects of their design, including the buildings' height, width, diameter, number of floors, façade panels (in Astana's case), and slab rotation (in the Absolute Towers). Regarding the Astana case study, for a better thermal performance of the building, the organization of the panels requires an analysis of the sun exposure. In the Absolute Towers's case, the buildings have non-ortogonal shapes that also benefits from an automated analysis. We analyzed the models using Rosetta's Radiance back-end with a Radiation Map metric.

3.1. COMPARING APPROACHES

In order for the model to be analyzed by DIVA it first needs to be prepared. This preparation involves introducing additional objects, adapting the geometry of the building elements, or restructuring the arrangement of layers. In the end, the model that is used for analysis is not the same that represents the actual building. This causes a maintenance problem, as all changes in the design need to be propagated to either models, or, alternatively, the preparation of the updated model for analysis needs to be repeated. Both options have considerable drawbacks. By making a new Rosetta back-end that automates analysis, the speed of the process is increased and possible setup mistakes are avoided. Moreover, in the event that the analysis options are the same for every iteration of the building, there is no need to re-introduce these options.

3.1.1. Overcoming Setup requirements

When initiating the setup of the model for analysis in Rhino, DIVA requires a ground plane that is composed of an adequate material. However, it is frequently the case that the ground plane is not part of the original model and, thus, the designer might forget to include it. Moreover, despite the considerable influence that the ground plane might have in the analysis, there is no guidance regarding its appropriate size. The same problem happens when using the DIVA-Grasshopper plug-in, as no information is provided regarding whether the ground plane should be modeled, or how it should be modeled. For cases like this, the automatic creation of the necessary surface for the analysis facilitates the analyst's task and speeds up the process of setting up the model. Using our Radiance back-end for Rosetta, the ground plane is automatically generated and its size is computed according to the size of the bounding box of the building. Furthermore, the ground plan will be assigned a default material, which can be easily changed by the designer.

When constructing a 3D model, the designer usually creates most of it using solid objects. DIVA, however, requires all elements for the analysis to be mere surfaces, poly-surfaces, or meshes. If these conditions are not met the program either refuses to perform the analysis or presents distorted results. This means that users that create models using solid objects must simplify them before analysis, e.g., by transforming solids into surfaces. Our approach automates this process by generating the elements in the model according to the requirements of the analysis tool. The user may program using slabs, beams, glass, etc., but, depending on

the back-end being used, those operations will generate solid objects or the corresponding surfaces. In the case of the Radiance back-end, only the relevant surfaces are generated.

When using DIVA-Grasshopper it is possible to execute the analysis on boxes and other solid objects. This represents a considerable advantage when compared to DIVA for Rhino since the user does not need to manually introduce changes to the model. However, in this case, the analysis grids cover all faces of the surface. This can be a disadvantage if the user only intends to analyze one part of the building. Moreover, by having additional surfaces to analyze, the process becomes more time-consuming.

3.1.2. Dealing with Materials

In order to specify the building materials, both DIVA and DIVA-Grasshopper associate materials to layers. This forces the designer to classify the geometric elements according to their material, which can be tiresome and might invalidate an existing layer organization. In Rosetta, materials are not associated with layers. Due to its CAD-BIM portability, all models produced in Rosetta benefit from the BIM approach to material information. Even if the geometry is meant to be generated by a CAD tool, like Rhino, the user can take advantage of default BIM families. As such, Rosetta contains all of the model's material data that is needed for the analysis despite generating only simple geometric elements in the chosen CAD application. For analyses, instead of using layers, the list of materials is extracted automatically from the generated model. This results in the analysis utilizing the actual materials that the designer selected for each element or the materials that were assigned by default.

3.1.3. Dealing with Non-Planar Surfaces

Most simulations offered by DIVA are node-based, meaning that a grid of points must be created to represent sensor nodes placed where the light levels should be evaluated. For each surface, DIVA assigns a single normal vector and computes the location of the sensor nodes at a given distance from the surface, along the direction of the normal vector.

DIVA's method for node distribution is a reasonable course of action when the model is made of boxes because each surface will be a rectangular plane and, thus, can be described by just one normal vector. Unfortunately, this method is not adequate for non-planar surfaces, which require a vector field. In DIVA's defense, it should be mentioned that the tool's documentation explicitly mentions that "complicated geometry can be pre-meshed before running the metrics." However, no indications are provided regarding this process and it is possible that the designer will not even know which geometry fits in the "complicated" category. Moreover, pre-meshing is yet another manual step that needs to be re-done every time the model changes. Unfortunately, failing to provide a proper description of the surfaces in the model can have a considerable impact on the quality of the analysis. As it happens with most software tools, if the provided description of the model is not accurate, the results will be incorrect, although that might not be obvious for

the designer.

For the final version of the panels from our first case study, the wrapping façade of Astana Library must be analyzed as a whole. Figure 3.A shows the results, of the node's placement of the library's façade, completed in DIVA without the pre-meshing step. As is possible to see, the normal vectors were incorrectly computed for almost all parts of the surface, thus making the location of the analysis sensors incorrect for significant fractions of the building envelope. This, in turn, causes both an incorrect analysis and an incorrect visualization of the results in which DIVA misorients the color-coded quadrangles.

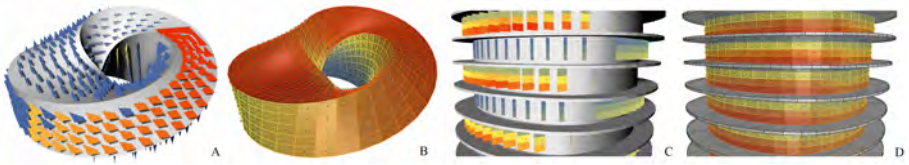


Figure 3. Nodes generated by DIVA and by Rosetta and resulting analysis' color-coded quadrangles in both case studies.

On the other hand, in Rosetta's Radiance back-end, each non-planar surface is automatically meshed according to the node separation, without the designer needing to be aware of this process. Moreover, for each surface, the corresponding vector field is computed, and the correct location and orientation of the sensors is provided to the analysis software. As is possible to see in figure 3.B, all nodes were placed with the same offset from the given surface and the color-coded quadrangles produced by the algorithmic analysis are correctly placed. This contrasts with the placement done by DIVA whereby half of the sensors were located beneath the surface. A similar scenario was encountered when performing the analysis in our second case study, the Absolute Towers. The goal was to analyze the radiation received by the glass walls on each floor. However, these elements are also non-planar and, as DIVA assumes a single normal direction for the entire surface, the color-coded quadrangles were also misplaced. The resulting analysis, presented in figure 3.C is, therefore, equally unreliable. In order to solve this problem, it would be necessary to rebuild the curved surfaces as sets of sufficiently small planar surfaces, an additional laborious step for the designer that is not needed in our approach, allowing for the correct analysis presented in figure 3.D.

3.1.4. Visualization of the Analysis

One of the important limitations of DIVA (or DIVA-Grasshopper) is that it only works in Rhino. On the other hand, the Radiance back-end for Rosetta is independent of the back-end that is used to visualize the results of the analysis. This means that it becomes possible to use whichever back-end the designer prefers. In figure 4, we can see the analysis results visualized in both Rhino and AutoCAD back-ends.

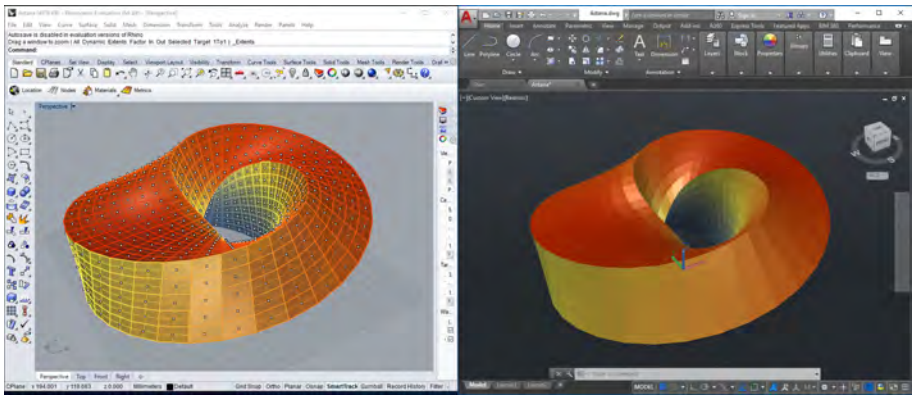


Figure 4. Analysis results generated in AutoCAD and Rhino.

Another important feature is that the analysis results are cached. Given that an analysis can take minutes or even hours to run, it is important to avoid wasting time. To this end, we cache the analysis results, so that when the model did not change relative to the previous analysis, the analysis results can be immediately retrieved with no impact in the performance of the GD process.

4. Conclusions

This paper presented Algorithmic-Based Analysis, a novel approach for the analysis of algorithmically generated buildings. The support the approach we extended a portable GD tool with additional back-ends for different kinds of analysis. Each back-end is specialized to generate a model that satisfy the requirements of each analysis tool without needing any further manual alterations from the user. This not only makes the results more reliable but also encourages architects to test a lot more variations of the intended design. We demonstrated the capabilities of our approach by evaluating the solar radiation on two buildings with complex geometries.

It is important to stress that our approach relies on a GD process and, thus, is not directly applicable to manually created designs. Given the flexibility allowed by Algorithmic-Based approaches, we consider this an advantage. However, it is also important to note that although GD can be very helpful in initial stages of the design process, it does not yet present a good return on the investment required to model a building up to its final stages, when a considerable amount of detail needs to be modeled.

Currently, the supported analysis tools include Radiance and DAYSIM and we are working on preliminary support for Energy Plus. We also plan to include additional back-ends, particularly, for acoustic and structural analysis.

As soon as the different back-ends are in place, we plan to use them for multi-objective optimization. Since the model and the analysis are generated in the same tool there is no information loss when changing the type of analysis. This means the results are more accurate and the building can be optimized according to its performance in all analysis back-ends. We have already tested this approach by

using the Monte Carlo method to optimize the façade of a building according to the Useful Daylight Illuminance (UDI) (Nabil & Mardaljevic 2006). We are now planning to implement more sophisticated optimization algorithms.

Acknowledgements

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ESTABLISHING PARAMETRIC RELATIONSHIPS FOR DESIGN OBJECTS THROUGH TANGIBLE INTERACTION

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Abstract. This paper presents a method for translating physical interaction with design objects into parametric relationships. A framework of the method is created to automate the generation of parametric equations as modeling constraints. The prototypes developed for this work link digital models with their physical counterparts to create a hybrid and tangible interface that enables user interaction. The prototypes investigate linear and non-linear types of object relationships for creating parametric models. The results demonstrate a novel approach in architectural design that assists users in creating complex geometric relationships through intuitive interaction.

Keywords. Physical Computing; Parametric Design; Building Information Modeling; Tangible Interaction.

1. Introduction

Parametric design in a broader sense is an algorithmic approach to establish interdependent geometric relationships for generating architectural forms (Woodbury 2010). The process is inherently mathematical in nature, and with advances in digital design tools, it has been possible for architects to visualize and explicitly utilize mathematical logic in the design process (Stavric & Marina 2011). Since the appearance of the first digitized CAD system (Ivan Sutherland's Sketchpad), modeling tools have evolved to include a wider range of applications and procedures to setup geometric constraints. Each system - including: *Variants programming*, *history-based programming*, *Variational geometry and design*, *rule-based variants*, and *parametric features-based design* - offers its users distinct interactive and controlling features for parametric modeling (Monedero 2000). The formal practice of establishing such systematized geometric relationships and modeling constraints is achieved through text-based (e.g. Revit family editor, API, C#, Python, etc.) and/or graph-based (Grasshopper, Dynamo, etc.) programming applications. Algorithmic procedures enable the architect to translate design intents

into functional parametric systems using explicit mathematical expressions; nevertheless, the process requires specialized mathematical and programming skills, which often fall outside the architect's domain of knowledge (Stavric & Marina 2011). Research has shown that the lack of such skills results in limiting the architect's creative abilities (Kępczyńska-Walczak 2014), whereas the essential premise of design is the negotiation between the designer and the design object. For those reasons, the research presented in this paper proposes and demonstrates a method that captures and translates architects' intuitive interaction with physical design objects into mathematical equations to be utilized as constraints in digital parametric models. The method is tested and validated through a series of prototypes, with each composed of (1) a hybrid interface that links digital and physical models together, (2) a regression analysis method (linear and non-linear curve fitting functions) to automate the generation of object relationships in mathematical form, and (3) an architectural application utilizing the generated equations to create a parametric model.

2. Research Questions

Establishing object relationships in parametric models requires explicit use of mathematical logic to communicate design intents. The manual implementation of parametric equations in digital models is a challenging process, especially in the case of creating complex and non-standard architectural forms. The proposed research aims to address this limitation to improve the digital design workflow by answering the following questions:

- *What is the type of user-interface that can capture and translate design intents into object relationships to create a parametric model?* A common practice of establishing and controlling constraints in a digital model is done through text-based or graph-based applications. However, earlier research suggests that a hybrid interface provides a more flexible form of physical interaction to communicate a design intent and to manipulate a parametric model in the digital environment (Al-Qattan et al. 2016). Therefore, the proposed research will develop and utilize a hybrid user-interface to generate and setup constraints in digital models.
- *What type of parametric relationships can a hybrid user-interface represent physically and generate digitally?* Object relationships could be portrayed as linear and non-linear in nature. Through prototyping, the research will investigate the ability to generate both types of relationships through physical interaction, and illustrate which mathematical equations are of value to the design process when creating a parametric system.

3. Previous Work

Existing works utilizing tangible interfaces demonstrate unique opportunities to improve the digital design workflow, and users' perception of space and geometry. They process user and/or environmental data to control and manipulate modeling parameters. However, such examples operate through predefined parametric setups, i.e. architects establish object relationships beforehand. Conversely, the pro-

posed work demonstrates a novel approach in creating design object relationships, by enabling the hybrid system to generate the mathematical information required to construct the parametric model. Reversing form and geometry into their mathematical definition is a common practice in the fields of engineering, mathematics, computer science, statistics etc. Software packages utilizing methods for regression analysis such as Math.Net Numerics (Ruegg et al. 2016) have streamlined the process of generating mathematical equations depicting data correlation. Another example is *Trendline* in Microsoft Excel, a technique used to find the best-fit curve (linear, polynomial, logarithmic, etc.) for a set of data points. Regression analysis for design applications is found in the Grasshopper Plug-in *Mantis*, which operates by linking parametric workflows with Wolfram's Mathematica (Zaghloul 2013). Examples of work utilizing Mantis, and Math.Net Numerics with text-based and graph-based programming (such as C#, Python, etc.) have shown the possibility of extracting mathematical information from specific types of geometry. Therefore, the proposed research finds that incorporating such tools in a digital design workflow will provide new means to discover and extrapolate relational patterns and mathematical logic for establishing complex parametric systems.

4. Research Significance

The proposed method enables architects to establish object relationships in digital models through their intuitive interaction with physical objects. The workflow utilizes a data mining process (regression analysis) to generate mathematical equations as the relationships. This approach releases the architect's burden of creating complex mathematical equations from scratch when modeling a parametric system. This study contributes to the future application of machine learning in the context of design. Further development may ultimately create a system capable of interpreting design intents, learning user preferences, and most importantly, enabling collaboration between the architect and the machine in the process of generating design options, facilitating parametric simulation, and design optimization.

5. Prototyping

Each prototype investigates a type of: (1) kinematics, (2) object relationships, and (3) regression analysis procedures; and is composed of a digital modeling environment and an *artifact*. The artifact is the tangible part of the interface that consists of an architectural representation (a design object) and a control system (sensors, actuators, and a microcontroller). The process is validated by monitoring objects' geometric response in both environments using the generated equations.

5.1. PROTOTYPE 1

Prototype 1 investigates a *linear* relationship of object parameters as an example of design intent. The experiment is conducted into two phases: (1) data logging and generating the mathematical equation, and (2) setting up the equation as a constraint in the digital model. The set of tools utilized for this experiment are categorized into two groups:

- *Software tools* for (1) modeling: Revit (Autodesk BIM authoring tool) and Dynamo (visual programming environment for Revit); (2) programming: IronPython (programming language); (3) linkage: Firefly plugin for Dynamo (Payne & Johnson 2012); and (4) data management: MS Excel.
- *Hardware* tools for creating an integrated circuit of electrical and electromechanical components to establish the users' interactive control system include: a mini servomotor, two rotary potentiometers, and a microcontroller type Arduino UNO.

The prototype consists of a BIM model composed of an array of three Revit family panels, and an artifact composed of a control system and three corresponding physical panels (figure 1).

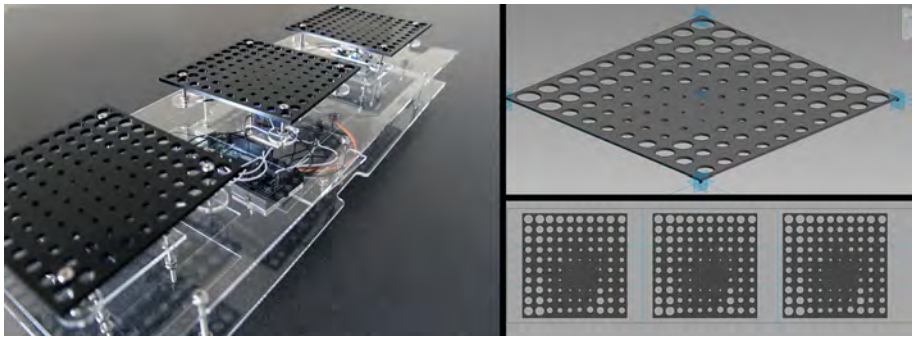


Figure 1. Artifact with panels (left) and corresponding Revit family panels (right). The panel array in Revit (lower right) is linked to the artifact in this experiment.

The prototype is operated by having the user physically rotating panels 1 and 3 horizontally (panels at the opposite ends of the artifact). Each of the two panels are attached to a *rotary potentiometer*, a sensor that monitors changes in the panels' angles of rotation. Sensor values will be used in a *linear* regression analysis to generate a mathematical equation depicting the panels' relationship. Following in the process, is parametrizing the equation and setting it up as a constraint in the digital model. The equation will be used to calculate the angles of rotation for Panel 2. In summary, the workflow for Prototype 1 includes the following tasks: (1) linking the BIM model and the artifact through Firefly, (2) performing a linear regression analysis, (3) generating the parametric equation, and (4) calculating the angles of rotation for Panel 2 and sending the values to both the digital model and the artifact (figure 2).

In Phase 1, linear regression analysis requires data samples to find the best fit curve, establish data correlation, and generate the mathematical equation. The rotary potentiometers attached to the panels provide data samples when rotating Panel 1 and 2 manually from 0 to 180 degrees, i.e. Panel 1 is rotated by {X1, X2, X3} degrees and Panel 3 rotated by {Y1, Y2, Y3} degrees, respectively. Once the two panels are rotated, sensor values are recorded and stored in a CSV file (figure 3).

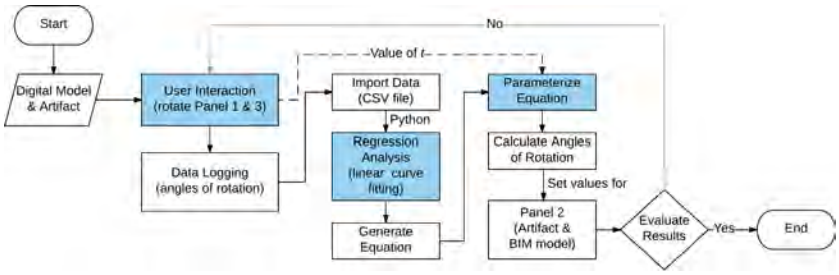


Figure 2. Workflow for Prototype 1.



Figure 3. Panels in their order (left); data logging process for regression analysis (middle); and user manually rotating Panel 1 (clockwise) from 0 to 180 degrees (right).

In Phase 2, the CSV file is imported in Dynamo for regression analysis. The regression analysis procedure is programmed using IronPython and integrated in the Dynamo workflow. The analysis procedure will calculate two values the *Slope* (equation 1) and *y-Intercept* (equation 2) using the following equations (Yan & Su 2009):

$$m = \frac{\sum[(x_i - \overline{x})(y_i - \overline{y})]}{\sum\left[(x_i - \overline{x})^2\right]} \tag{1}$$

$$b = \overline{y} - (m\overline{x}) \tag{2}$$

The format of the linear equation used for establishing panel relationship is based on the *Point-Slope* from of the line equation ($y = mx + b$), where m is the Slope and b is the y-Intercept. The generated equation at this point describes the relationship between Panel 1 and 3, excluding Panel 2. The angle value required to rotate Panel 2 is obtained by solving x and y using the generated line equation. Nevertheless, the current process does not support parametric functionality that is required to control the panel array. Therefore, an additional procedure in Dynamo was developed to parametrize the equation. The process includes setting t as an independent variable to solve x and y ($x = t$, $y = mt + b$). The *t* value in the equation is substituted with the angles of rotation obtained from the rotary potentiometer attached to Panel 1. The calculated results using the parametric equation provided all the possible interpolations (angles of rotation) for rotating Panel 2 in between the other two panels. At this stage, the parametric system is setup, and further changes in the angles of rotation for Panel 1 and 3 will automatically update Panel 2's rotation in both the BIM model and the artifact. In the artifact, Panel 2 will rotate using the mini servomotor, and in the BIM model by using an instant *Angle* parameter (figure 4).

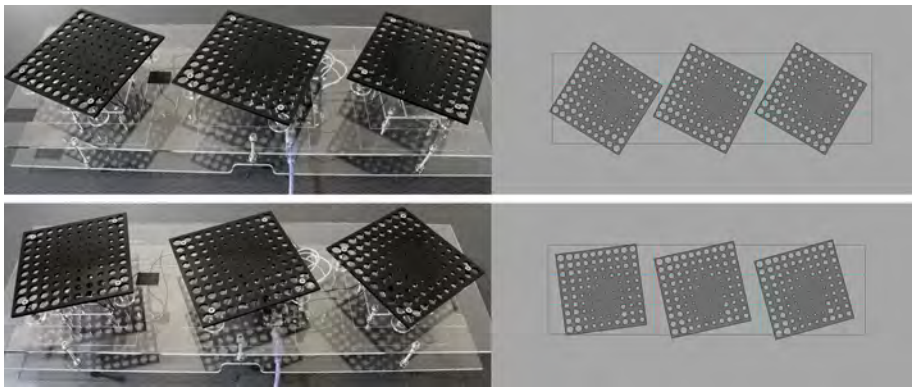


Figure 4. Physical interaction with Panel 1 and 3 will automatically rotate Panel 2 using the generated parametric equation.

Prototype 1 shows that utilizing linear regression analysis in this framework helped in mathematically deducing the relationship between physical design objects, and setting up a parametric relationship between the panels in both the digital and physical models.

The purpose of the prototype is not to simply determine the rotation angles of Panel 2, but to determine the linear function and its coefficients representing the parametric relationship of the array of panels. Once the relationship is setup in the digital model, the architect can make changes to the model and the design intent will remain intact.

5.2. PROTOTYPE 2

The second experiment investigates *non-linear* object relationships as a more complex example of design intent. The work involves a two-phase process similar to the previous experiment to generate the mathematical equation and establish the parametric relationship between design objects. The set of tools chosen for this experiment are:

- *Software tools* for (1) modeling: Rhino (3D modeling environment) and Grasshopper (visual programming environment); (2) programming: C# (programming language); (3) and linkage: Firefly plugin for Grasshopper.
- *Hardware tools* for creating the control system include: eight linear soft potentiometers (ribbon sensors) and a microcontroller type Arduino MEGA.

The prototype consists of a Rhino model of an architectural space with its roof made of an array of louvers, and an artifact composed of a control system and a physical representation of both the space and louvers (figure 5). In the artifact, each louver is connected to a ribbon sensor, which is located on the model's side. The sensors measure the vertical distance - in inches - between each louver and the model's floor, and send the values to Grasshopper through Firefly. In Rhino, each vertical distance value is represented as a point on the XZ plane to indicate the location of the physical louvers.



Figure 5. Hybrid interface developed for Prototype 2.

The points generated by the sensors are used for performing the non-linear regression analysis. The procedure utilizes a polynomial curve fitting function to generate the mathematical equation depicting the louvers' layout, which will be used later to setup the parametric model (figure 6). Regression analysis in this experiment is programmed using C# and Math.Net Numerics, and similar to the previous experiment, the procedure is integrated with the visual programming workflow. The prototype in this experiment has a unidirectional link, i.e. architects provide the system with analog data by moving the physical louvers to generate responses in the digital model; whereas Prototype 1, has a bidirectional link that enables digital and physical interaction and response.

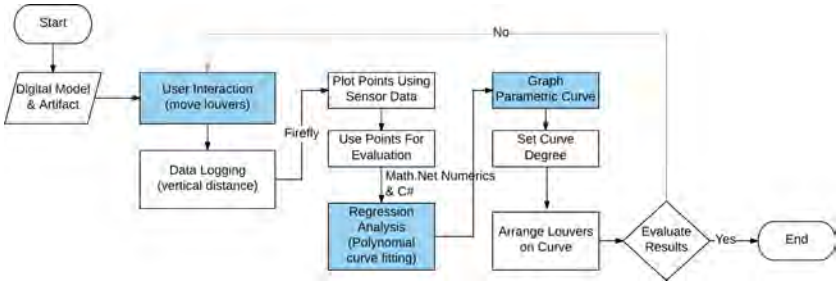


Figure 6. Workflow for Prototype 2.

Non-linear regression analysis in Prototype 2 will assist in generating the mathematical equation that depicts complex object relationships. The equation used for this work is assumed to be a polynomial with a single variable x (Tan 2011) as shown in equation 3:

$$a_n x^n + a_{n-1} x^{n-1} + \ldots + a_0 = 0 \qquad (3)$$

In Phase 1, the vertical distance values are plotted in the Rhino scene as points shown as crosses, and each point is labeled with its corresponding ribbon sensor (figure 7, graph 1). A total of eight points are generated for the eight physical louvers. The programming workflow using Math.Net Numerics will find a polynomial curve that best fits the sensor points (figure 7, graph 2). In Phase 2, the polynomial function generated by the regression analysis is used to layout and move the louvers in Rhino parametrically (figure 7, graph 3).

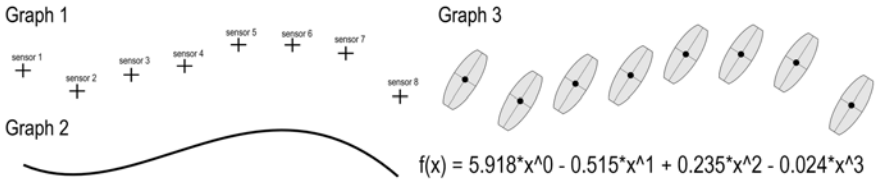


Figure 7. Regression analysis process and implementation of the parametric polynomial curve.

The parametric polynomial curve is tested in this workflow by letting the architect reconfigure the louvers' layout in the artifact (figure 8). The results show that the louvers' layout in Rhino updates instantaneously with the architect's real-time interaction with the physical objects. The louvers' reconfiguration shown in figure 8 generates a polynomial curve of degree 4 ($f(x) = 7.057x^0 + 0.122x^1 - 0.540x^2 + 0.123x^3 - 0.007x^4$)



Figure 8. Testing the workflow, the generated equation in this example is a polynomial of degree 4.

The workflow in Grasshopper enables the architect to fine-tune the louvers' layout in Rhino to match their physical counterpart by increasing or decreasing the degree of the generated polynomial equation. Figure 9 shows the process of fine-tuning the polynomial equation from degree 4 to 8 using the louvers' layout previously shown in figure 8. The results demonstrate that a degree 8 polynomial is the best fit, yet high degree order may not be desirable in a design context due to its complexity for construction and representational quality.

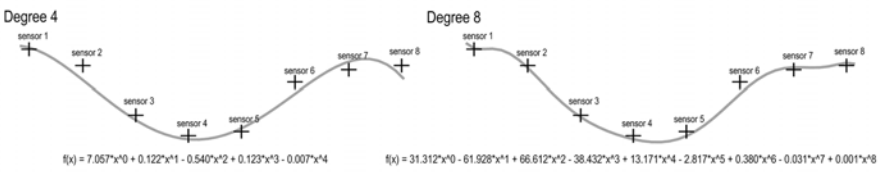


Figure 9. Fine-tuning of the polynomial curve by increasing the polynomial from degree 4 to 8.

The integration of the parametric polynomial curve within the developed programming workflow assists the architect in making further changes to the digital model while maintaining the design intent. For example, if the number of louvers is to be changed, the updated array will be automatically re-located along the polynomial curve. If the coefficients of the polynomial are used as parameters, we can fine-tune the curve by adjusting some of the coefficients to obtain different design configurations.

Note that this method of creating curves for parametric design is different from the widely used NURBS curve generation method, where the user's input points are used as control points for creating low degree Bézier curves that are pieced together to form a complex curve. The purpose of this experiment is to demonstrate that physical interaction between designers and the artifact can assist in generating complex relationships to create parametric models (a parametric curve in this example).

6. Discussion

The two prototypes demonstrate the possibility to automate the generation of mathematical equations for two types of object relationships, linear and non-linear, by translating architects' intuitive interaction with physical design objects, and without the need to possess advanced mathematical skills.

The two experiments test the method to create both simple and complex (linear and non-linear) geometric relationships in mathematical equation forms. The approach is applicable in the conceptual design phase where architects seek to explore dynamic, and non-standard forms and geometric configurations. The prototypes can not only translate physical transformation information into digital models as existing systems can do, but also capture and translate the design constraints or relationships into digital models to make them parametric and embedded with design intents. The method potentially provides great value to BIM and parametric modeling tools (Revit/Dynamo, Rhino/Grasshopper, Digital Project, CATIA, etc.) to enhance their parametric modeling capability. The benefit of the proposed work lays in its ability to overcome the challenges associated with manual implementation of parametric constraints, and focusing on inviting architects' haptic and visual senses in the digital design process.

7. Conclusion

The proposed work considers physical interaction as an alternative method for establishing parametric models, in addition to computer programming, which is of significant difficulty for architects. The prototypes demonstrate a method that is capable of (1) determining the type of object relationships, (2) generating parametric equations, and most importantly (3) its application in the context of design.

The focus of this work is on translating tangible interaction into parametric constraints for digital modeling. Once a parametric model is constructed further studies using optimization algorithms will be done to address certain architectural conditions related to aesthetics and performance. It is expected that the proposed method can assist architects in reducing the extensive effort associated with encod-

ing mathematical procedures in the programming workflow. The use of regression analysis with a simple data set has shown the possibility of constructing parametric models. Further development of the method will provide users with a system capable of implementing more complex design intents. Additionally, the work will further investigate the translation of deign intent between the digital and physical environments. As seen in the experiments, some discrepancies occurred, which were caused by human users' inaccuracy of spatial perception and motor skills.

Acknowledgment

We would like to thank our colleagues at Texas A&M University for their help and support, Dr. Saied Zahrammer for his assistance in Python programming and Assistant Professor Dr. Negar Kalantar Mehrjardi for providing us with the digital fabrication machinery.

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SEAT SELECTION SYSTEM FOR THEATRES AND CONCERT HALLS BASED ON AUDIO-VISUAL INTEGRATION TECHNOLOGY

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Abstract. It is of great significance to establish the virtual visual/audio simulation in building environment or indoor auditorium, as this is also a key issue which has drawn attention from other research fields including computer-aided design, virtual reality and acoustic simulation. This paper introduces the architecture and realization of a seat selection system based on audio-visual integration technology and the subjective preference test based on the seat selection system. The visual/audio subjective evaluation experiments on Xiamen Concert Hall and Ferrara Opera House were carried out, the experiments show that visual-audio factors have impact on the visual-audio preference and subjective evaluation of concert halls and theatres. The combined effect of acoustic and non-acoustic parameters (such as visual factors) on hearing and the perception of acoustics is also discussed in the paper.

Keywords. Virtual Building Environment; Audio-Visual Integration; Subjective Preference of Seats.

1. Background

It is of great significance to establish the virtual visual/audio simulation in building environment or indoor auditorium, as this is also a key issue which has drawn attention from other disciplines including computer-aided design, virtual reality and auditorium acoustics.

Studies have shown that, when humans perceive the objective world, about 60% of the information is acquired via vision, about 30% via auditory sense and the remaining 10% via tactile, olfactory and other sense (Wang et al. 1996).

As for simulation under a computerized condition, the research tended to focus more on the visual channel, while in the practical application the auditory channel is also important (Blauert 1983). The studies have shown that the auditory information helps enhance the truth and immersion of virtual reality, while the visual

cues, as a complement to the auditory sense, is also helpful to make the acoustic environment more real and reduce the acoustic localization confusion (Begault 1983).

Yoichi Ando has done a great deal of researches on subjective evaluation of auditorium acoustics and introduced the first seat acoustic selection system in the world, which was established for Miyama Concert, However, this system was only aimed to realize the acoustic channel (Ando 1998).

While other studies, from the perspective of current computer application, aim to design simplified sound processing mechanism to realize some 3D audio effects for supporting the game application etc. For example, Microsoft's Direct Audio and Creative's OpenAL support the 3D positioning of virtual spatial sound and reverberation effect of virtual space. However, such applications simulate mainly the effect instead of a real physical environment, and are mostly used for commercial games and multi-media applications. It is far different from virtual "reality" and can hardly meet the professional acoustic requirements.

For the concert hall or theatre design, visual effects and sound effects are equally important to the show, two factors need to be studied in the meantime. The subjective preference test for visual or audio performance is practical method for the concert hall or theatre design and evaluation. But the test is difficult conducted in real environment because the test need to be repeated many times, so the virtual environment simulation system is more suitable for Lab researches.

Compared to aforesaid researches, there is much less research on seat selection system based on audio-visual integration (Jeon et al. 2008), in particular the creation of the application system with the virtual reality features.

The paper discusses the research on and realization of audio-visual integration in virtual environment. It introduces the development of seat selection system based on this technology. The subjective preference test of the seats based on the seat selection system is also discussed.

2. System Realization Framework

The system realization mainly involves the followings:

1. Build a 3D computer visual model of auditorium and binaural impulse response database of different locations (via actual measurement or software simulation).
2. Develop a program for 3D visual rendering engine and fast sound signal convolution to realize the 3D visual-audio effect in virtual auditorium environment.
3. Build an interactive interface with characteristics of virtual reality (use the interactive devices such as Head Mounted Display (HMD) and 3D position tracker).
4. Establish the synchronization mechanism of sound and image channel. With the seat selected by the user on the auditorium seating layout or the 3D location information acquired via a 3D position tracker, the system rapidly renders the corresponding visual image and processes the sound signals to realize the rapid visual representation and rapid retransmission of the sound field.

3. System Realization

Figure 1 is the schematic diagram of audio-visual integration system. The 3D engine will read the 3D auditorium model and user's 3D location interactive information (by means of position tracker or mouse selection on auditorium layout plan). Meanwhile, the Sound Processing Module will read the impulse response information of the selected seat, and, coupled with the "dry signal" recorded in the anechoic room, generate the corresponding acoustic signal via convolution. The 3D image information and relevant acoustic signals are then transmitted to 3D image buffer and sound buffer respectively. They would then be replayed simultaneously in HMD or large screen and hi-fi headphone to finally present the audio-visual effect to the user.

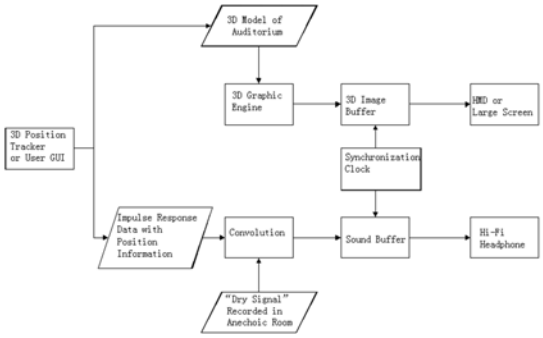


Figure 1. Schematic diagram of audio-visual integration in virtual auditorium environment.

The realization of the system consists of three modules: 3D Scene Rendering Module, 3D Sound Module and System Synchronization Module.

3.1. REAL-TIME 3D SCENE RENDERING MODULE

3D Scene Rendering Module is realized based on OpenGL. For a real-time 3D rendering engine, 3D geometry and texture data is very large, so it is essential to 3D engine as for how to manage, display and optimize these data. Though there are a lot of data structure forms for 3D scene management, scene graph is one of the effective scene management models.

In this project, Bounding Volume Hierarchy (BVH) is used to organize spatial data sets for 3D engine, which refers to the organization method of OpenSceneGraph (OpenSceneGraph 2009). "Bounding volume" means to enclose one or a group of objects in a simple spatial body in order to enhance the speed of various tests.

The scene tree not only manages relevant information of the entire scene, but also conducts culling and adjusts the order of the nodes before submitting the rendering operation to low-level interface. On the other hand, the realization of scene graph encloses a great number of low-level rendering and data operations, making user interface easier to use. The object-oriented features of the realization of scene graph also make it easier for users to operate 3D objects on bigger coarseness while

reducing or eliminating platform relevance of the system.

In the meantime, Christie's 3D projection system, which features stereoscopic technology, is used for 3D display to enhance the sense of presence. To create stereoscopic pictures, graphics card of Qudro FX Series is adopted based on OpenGL quad buffered stereo display technology. See figure 4a for hardware configuration.

3.2. 3D SOUND MODULE

The primary function of 3D Sound Module is to get the saved binaural impulse response according to user's current position information, and do convolution with dry signal, to send the result signal to the sound buffer and playback. This module is realized with C++ with reference to corresponding algorithm.

The indoor acoustics studies have shown that a room in the building can be deemed as a Linear Time Invariant (LTI) transmission system (Vorländer 2008). For a LTI system, with a input signal *x(t)*, the system will output a signal *y(t)*, which equals the convolution of the input signal and the impulse response h, i.e.:

$$y(t) = x(t) * h(t) = \int_{-\infty}^{+\infty} x(\tau)h(t-\tau)d(\tau) \tag{1}$$

For the discrete signals, it is:

$$y[n] = x[n] * h[n] = \sum_{k=0}^{N-1} x[k]h[n-k] \tag{2}$$

For the acoustic simulation and audibility of auditorium, binaural system has to be considered. The acoustic wave scattering effect caused by human head and pinna and the resulting binaural signal difference can be described with Head Related Impulse Response (HRIR) or Head Related Transmission Function (HRTF).

Convolution can be calculated directly in time domain. Since the original signal is generally a long signal, direct convolution is a very time-consuming calculation. Therefore, blocking convolution (or batch processing) is recommended. As for block convolution, overlap-save method or overlap-add method can be adopted (Ingle and Proakis 2008).

Another purpose of partitioned convolution is in the hope to better use computer resources in parallel processing. For CPU, multi-threaded processing can be adopted, especially for multi-core CPU system.

Under normal circumstances, the length m of dry signal x is greater than the length n of the impulse response h, then x can be divided by each length of m into multiple continuous segments. The last segment will perform zero padding operation.

By calculating the convolution of each dry signal segment with the impulse response, the results of partitioned convolution $y_0 - y_m$, $y_{m+1} - y_{2m}$, $y_{2m+1} - y_{3m} \cdots$ are worked out; and finally, by adding the *m-1* value before and after each result *y* to the *m-1* value before and after it respectively, the final result of convolution is obtained. The whole process is to perform convolution while playing in the form of flow in a multi-threaded process. The specific process is shown in figure 2.

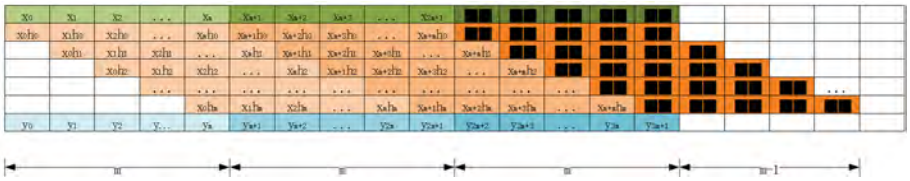


Figure 2. Diagram of partitioned convolution.

In this paper, further tests are conducted on sound signal convolution processing in GPU which is firstly designed primarily for graphics computing. The major difference between GPU and CPU lies in that more ALU calculation units are added to GPU with less control units and Cache. Therefore, GPU is far stronger than the CPU in calculation but not suitable for complex logic control, thus has its advantage only for highly intensive parallel computing.

To realize the convolution computing of one-dimensional signals in GPU, the basic idea is to assign partitioned convolution to different thread blocks in GPU, and assign multiplication and addition of signal sequence to the thread of each thread block.

Convolution can be also processed in frequency domain by adopting CUFFT library optimized for GPU (Nvidia 2009). Comparison tests are performed on Nvidia FX5600 and Intel 2.66G quad-core Xeon processors. For single-precision floating-point sequence convolution experiment, it is nearly 160 times faster than CPU processing, hence it can be applied to real-time convolution processing.

3.3. SEAT SELECTION INTERFACE AND AUDIO-VISUAL SYNCHRONIZATION

Seat selection interface enables an user to locate himself in a 3D scene by choosing a seat on the seating layout and to obtain necessary seat information, including the numbers of row and column. Meanwhile, when a user selects a seat, the system should be able to retrieve indoor binaural impulse information corresponding to this location in a synchronized way.

A Map class is developed to encapsulate various functions including the display of the plan, marking of seats etc. The plan of each floor is displayed in the form of raster image. At the same time, another diagram, which is identical in terms of seating layout and seat dimension and locations, is created. This is called Mask Plan, Each seat is filled with colors determined by certain coding method. R value represents column, G value represents row, while B value represents the number of floor. Mask Plan is not displayed in user interface, as it means to help computer analyses the code value of pixel of the location which user has selected, hence easily determines which seat the user has selected and the retrieved relevant binaural impulse response data (figure 3).

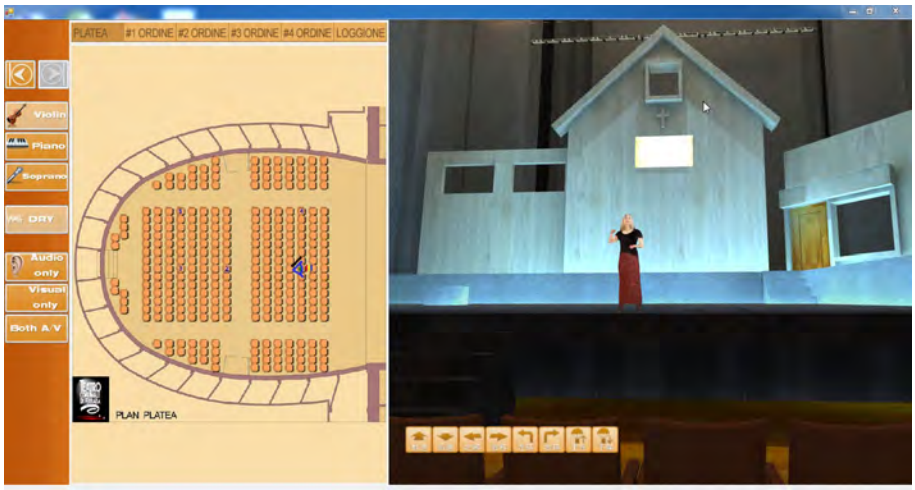


Figure 3. Interface of seat selection system.

4. Application of Seat Selection System Based on Visual-Audio Integration Technology

The subjective evaluation and preference theory of auditorium acoustics is one of the most important research topics in architectural acoustics. Since 1950s, many studies have been done on the objective parameters of auditorium acoustics and the correlations between and independence of these physical indices (Larsson and Kleiner 2012).

Another important research topic is the study on the combined effect of acoustic and non-acoustic parameters (such as visual factors) on hearing and the experience of acoustics. The existing studies have shown that vision does have important impact on hearing and affects people's judgment on distance, location of sound source and cordial degree.

A seat selection system based on audio-visual integration can be used as an experiment platform for studies on subjective evaluation of audio-visual mutual impact. The research team has already done subjective evaluation experiments on Xiamen Concert Hall and Ferrara Opera House, Italy based on the visual-audio integration simulation system elaborated in this paper (Sato et al. 2010; Sato et al. 2012) (figure 4).

Relevant visual-audio preference tests were conducted in the acoustic laboratory of SCUT (hereinafter referred to as Experiment 1, figure 4a and the acoustic laboratory of Faculty of Engineering, the University of Ferrara, Italy (hereinafter referred to as Experiment 2, figure 4b). Comparison subjective experiments were carried out in pair on 10 seat locations (figure 5).

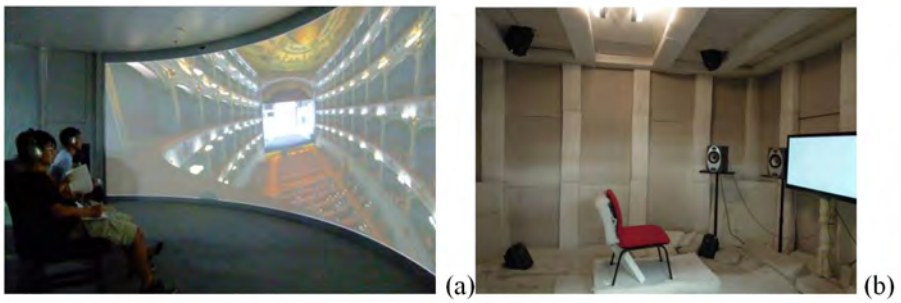


Figure 4. Laboratory settings. (a) Laboratory setting 1; (b) Laboratory setting 2.

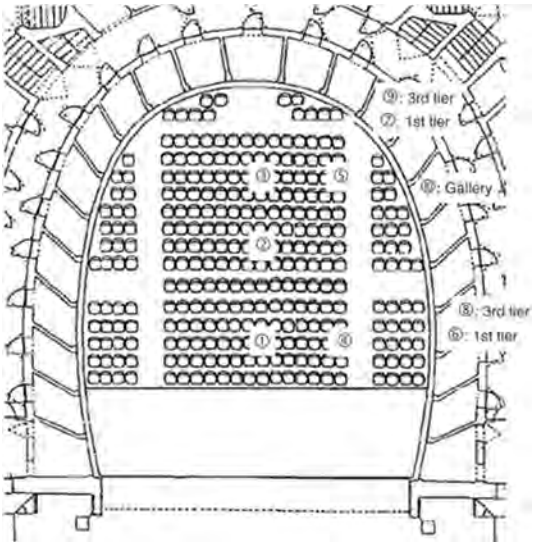


Figure 5. Seat locations selected for subjective tests.

To eliminate the impact on separately provided visual and auditory signals possibly brought by simultaneous feeding of visual and acoustic signals, the test sequence is decided as 1) visual signals only, 2) auditory signals only, 3) simultaneous providing of both visual and acoustic signals.

Experiment 1 adopted a large-screen stereoscopic projection system as its visual output, and a high-fidelity headphone as acoustic signal output. Experiment 2 adopted a 42-inch LCD monitor as its visual output, while sound channel was realized through six pairs of speaker array retransmission.

Although the participants of two experiments were very different in cultural background and native language, and the experiment conditions and equipments were also different, the preference results turned out to be similar. See figure 6 for details of results.

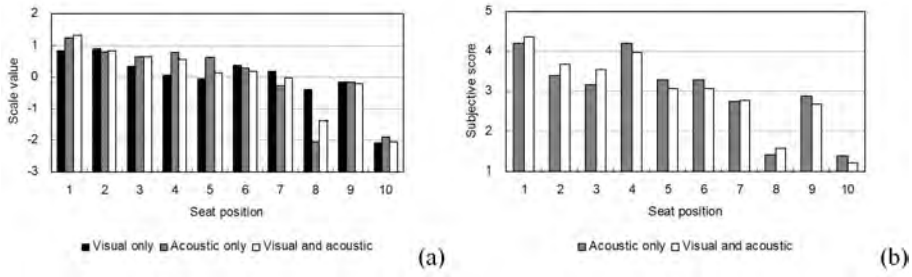


Figure 6. Preference values at different test conditions. Experiment 1; (b) Experiment 2. (No. 1 to No. 5 are stall seats and No. 6 to No. 10 are box seats).

The complete process of the test and data analysis have been reported in the paper (Sato et al.2012) and are not be described here.

The result of the study has shown:

1. The seat selection system based on visual-audio integration system and the various visual-audio preference tests conducted at different test conditions on the same basis show that visual-audio factors have impact on the visual-audio preference and subjective evaluation of concert halls and theatres.
2. The combination of acoustic and visual information makes participants easier to make preference judgment as compared to the audio signal only scenario and the judgment and the result of preference are more stable. In test, the chance of circular triads has been greatly reduced.
3. The correlation between preference results of audio signal only scenario and visual-audio integration scenario is higher than that between the visual signal only scenario and visual-audio integration scenario. The research of of Joen et al. (2008) has shown that in cross-modal test, audio and visual cue factors are discovered to both have contribution to the overall visual-audio impression of seat preference in concert halls and theatres, but audio factors have greater contribution than visual factors, the experiments have proven such conclusion.
4. As for the preference to the visual factor, the seats near the central axis of the auditorium have higher preference values than those on the sides, and the lower box seats have higher preference values than the higher ones. The preference value is negatively correlated to the geometric parameters and the distance between sound source and receiving point. The vertical angle is most correlated to the subjective preference value.
5. The most prominent factors affecting the selection of seats are Leq and C80. IACC has positive correlation with preference value, but the correlation is not obvious. Preference value of parameters related to spatial experiences, such as IACC, shall be further testified in subsequent researches and experiments.

It should be noted that the subjective evaluation and preference of auditorium is a complex process, the paper just establishes a testing prototype, the more detailed experiment should be done in next work.

5. Conclusion

This paper discusses the research on and realization of visual-audio integration technology for virtual environment, the application and subjective evaluation experiments based on visual-audio selection system. As discussed above, the subjective evaluation and preference theory of auditorium acoustics is one of the important research topics in architectural acoustics, in particular, the study on the combined effect of acoustic and non-acoustic parameters (such as visual factors) on hearing and the perception of acoustics.

This paper constructs an experiment framework for the application of virtual auditorium environment. For many detailed issues like the enhancement of interactive and immersive experiences of the system, or the adoption of individualized HRTF to improve the real experience, more and deeper studies are still expected.

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Design Process

P. Janssen, P. Loh, A. Raonic, M. A. Schnabel (eds.), *Protocols, Flows and Glitches, Proceedings of the 22nd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2017*, 169-179. © 2017, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

AGILE X UNISA PAVILION: AGILE PRINCIPLES AND THE PARAMETRIC PARADOX

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Abstract. The world is experiencing an ever increasing pace of change and yet our design processes typically follow a waterfall model that make can make change and adaptation difficult. Digital design approaches provide an opportunity to develop agile solutions that are more open to change in the design process. This paper proposes the development of immaterial architectures wherein the material expression is left to later in the design process when there is greater certainty. We describe a series of 3 workshops that employ aspects of agile software development methodologies into architecture. The workshops proposed 3 immaterial pavilions for Delft, Adelaide and Tianjin. This first cycle of three workshops resulted in the design, fabrication and installation of the Agile X UniSA Pavilion in Adelaide. This paper discusses the applicability of agile development methodologies to this process and details a series of adaptations to provide a set of appropriate agile development principles for architecture.

Keywords. Agile; Architecture pavilion; Immaterial architecture; Parametric paradox; Collaboration.

1. Introduction

Modernism dictates that design should be tailored to its materials. This belief has largely continued unchecked into contemporary digital design processes. This paper proposes an alternative approach that supports flexibility in the choice of material and fabrication systems. Parametric design systems provide flexibility in the design of buildings (Aish & Woodbury 2005). This should be extended to include flexibility in material and fabrication. However, designers of parametric systems typically lock in a specific material type (material system) into the design

system, which ensures reliance on a specific supply chain. This is a challenge because changes in the availability of the material can impact the cost and time that it takes to deliver an architectural project.

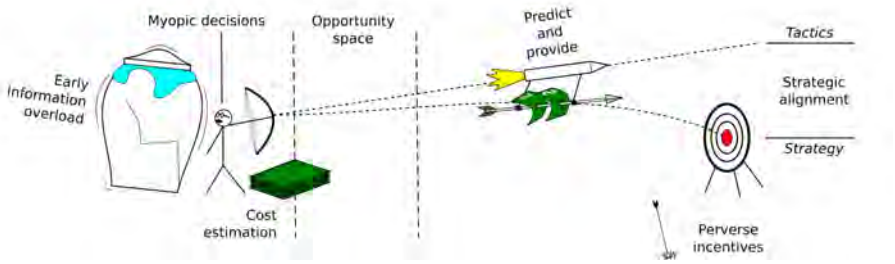


Figure 1. Common project planning paradoxes after Samset & Volden (2016) diagram by authors.

There are many similar paradoxes to be found in project planning (Samset & Volden 2016) (figure 1), whilst it is not possible to address all of them, this paper seeks to identify approaches to help designers to manage them. This paper argues that digital meta design systems could support a more 'agile' approach to material specification and procurement in architecture that could respond to material availability and, more relevantly, resource scarcity (McGinley 2015b). There are many paradoxes of front end decision making in project management (Samset & Volden 2016). These include that tactical success of a project does not automatically mean a strategic success. This can be because the tactical approach may be misaligned with the project strategy, or the success assessment focuses on tactical rather than strategic success. This can be seen in news media items that focus on failure as running over on time or budget, more than if it meets the needs for which it was intended. A project can therefore be a tactical success, i.e. on time and budget but a strategic disaster.

Samset & Volden reveal other paradoxes in project management that are relevant to architecture. These include a concern about an overflow of information in the early stages of the project that can make effective cost estimation, tactical and strategic decision difficult due to 'analysis paralysis'. This is compounded by the potentially myopic perspectives of the planners, predict and provide models that are designed only to satisfy the potentially poorly predicted future demand. Further investigation of the opportunity space may enable stakeholders to consider how to reduce demand rather than simply provision for it for instance. Some of these challenges may be able to be explored by expanding the opportunity space, however to achieve this the path dependence of the stakeholder's design decisions also needs to be challenged. Ultimately even with a robust conceptual model generated in the opportunity space, the paradox of strategic alliance says that 'the internal logic of causalities and the probabilities of realization' will result in erroneous solutions (Samset & Volden 2016). It therefore seems sensible that identifying design technologies and methods that are flexible and support exploration of the opportunity space as far into the project as possible would be beneficial to strategic success in architecture projects.

2. Parametric Paradox

Parametric models define and encode relationships in digital design components that enable designers to control the parametric design through the manipulation of parameters. The parameters that the designer of the parametric design system selects determines the opportunity space that the parametric design system explores. Parametric models are require additional work to be done at the start of a project and are reliant on the appropriateness of the parameters selection at the front end of the project (Yu et al. 2015). In this way are subject to the 'paradox of the opportunity space' described by Samset & Volden (2016) (figure 1). The argument for parametric systems is that they can augment a designer's ability to explore an opportunity spaces that can be predicted in advance. Furthermore, the development of robust parametric design systems could be used to adapt the design proposals in response to a required change in strategy from late emerging information. However, parametric design systems are frequently developed in an ad hoc manner that means we end up with 'spaghetti parametrics' that can be difficult to reconfigure to an adjusted design strategy beyond the scope of the parameters defined in the system (Davis et al. 2011). To address this, we need to apply robust and flexible development methodologies that produce high quality outputs and are appropriate to the design process.

3. Agile Development Methods

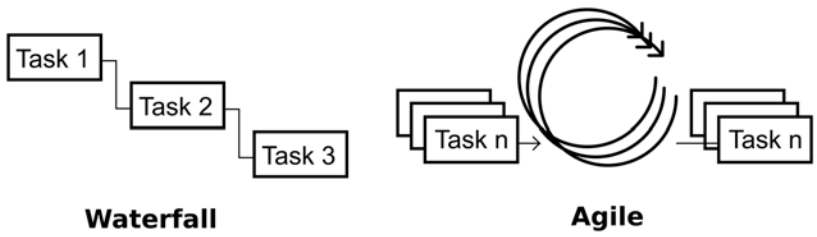


Figure 2. Waterfall vs. Agile development.

In response to an increase in the control of project managers and creativity crippling documentation requirements in software development at the turn of the 21st century, programmers developed a series of methodologies which were united under the manifesto of agile software development (Beck et al. 2001). The story of the development of Agile is well documented as are the techniques to employ it (Martin 2003). Agile is often compared to the more traditional 'waterfall' model (figure 2) wherein each of the main tasks are completed sequentially and are all planned up front. In Agile development the design progresses in sprints and the tasks are reviewed on a daily basis. These ideas were incorporated in the four values of the Agile Software Development Manifesto (Beck et al. 2001).

1. Individuals and interactions over processes and tools
2. Working software over comprehensive documentation

3. Customer collaboration over contract negotiation
4. Responding to change over following a plan

Agile development covers a range of approaches including, XP (extreme programming), Scrum, (Erickson et al. 2005) as well as others. Droste (2010) describes a process of applying agile development methodologies from computer science in architecture. The limitation of Droste is that it focusses on XP rather than more broadly on the principles of Agile development. This is important because there is much discussion in computer science about the most appropriate method of agile development. Therefore this paper focuses on the principles of agile development rather than a particular methodology.

The principles are summarised here as: Satisfy clients by early and continuous delivery of valuable designs (P1); Welcome changing requirements, even in late development (P2); Deliver working designs frequently (P3); Facilitate close, daily cooperation between stakeholders and designers (P4); Build projects around motivated individuals, and trust them (P5); Encourage face-to-face conversation as the best form of communication (co-location) (P6); Measure progress on working design systems (P7); Maintain a constant sustainable pace (avoid burn out) (P8); Focus on technical excellence and good design (P9); Maximise the amount of work not done (P10); Support teams to self-organise (P11); Reflect continuously on how to become more effective and adjust behaviour accordingly (P12).

4. A Hybrid Approach

There have been approaches previously to map the Agile development processes into design and design research (Conboy et al. 2015). Agile project management has also been proposed as a method to deal with resource scarcity and fluctuating availability in construction in the form of an 'Agile fabrication methodology' (McGinley 2015b). These approaches could be applied to frameworks to support more open architectural design processes by applying methods from computer science into digital architectural design (Schneider et al. 2010; McGinley 2015a). To answer this question we embarked on a series of design workshops to explore the application of agile development principles in architecture. The mapping was used to inform three workshops which proposed an 'immaterial' approach to digital design that decoupled the design from its potential material and fabrication systems. The following sections of the paper provide descriptions of the workshops followed by a reflection on how they performed in relation to the agile principles defined previously.

5. Agile X Workshops

The first workshop attempted to create immaterial pavilions that could adapt to the diverse contexts of Delft, Adelaide and Tianjin. The second workshop explored a parallel design process wherein students worked on the conceptual; design, detail and materiality systems in parallel. This resulted in a pavilion for Adelaide that could be conceptualized, materialized and fabricated in many different combinations. The final workshop incorporated representatives from practice with architecture and engineering students from UniSA. It resulted in the fabrication and

installation of the 'Agile X UniSA Pavilion' (figure 5) at ODASA (the Office for Design and Architecture South Australia). The three workshops are discussed in the following sections from the perspective of the Agile principles to identify how well the agile process fitted and was applied to the design context.

5.1. AGILE X 1 (AGILE FAB DELFT)



Figure 3. Overview of Agile X 1.

The first workshop ran over 5 days, hosted by Hyperbody Research Group at TU Delft. Students from University of South Australia (UniSA), Hyperbody, Tianjin University and Beijing Jiaotong University worked in 6 groups of 6. Each group had participants from each institution. 2 groups focused on the Beijing pavilion, 2 on the Adelaide pavilion and 2 on the Delft immaterial pavilion. On the last day of the workshop the intention was to materialize a tectonic detail within the pavilion. Due to time constraints this was not possible, but all groups did manage to adapt their immaterial design so it could be applied to the other 2 sites. This meant that we ended up with a set of 6 designs that could each be applied in the three contexts. In terms of agile principles, this workshop performed well in the facilitation of close daily collaboration (P4) as shown in figure 3. The groups were also self-organizing and maintained a constant sustainable pace (P8). The challenge with reviewing the agility of the workshop is that the agility was not extensively tested in this workshop. For instance, few changing requirements (P2) were placed on the participants beyond starting with a focus on a single site and then in the last days being asked to adapt their immaterial architecture so that it could adjust to all three contexts. In the end AX1 provided the 'front end' work that we needed to the support the other 2 workshops, but in itself was not very agile and produced a limited number of working design systems. That said there was constant and stimulating informal reflection on the process (P12) which helped to inform the following workshops.

5.2. AGILE X 2 (AX2)

The second Agile X workshop ran over 2 weeks in Adelaide, South Australia. 12 participants divided into 6 teams of which: 2 teams focused on the material systems of the pavilion; 2 focused on the design system; and 2 focused on the fabrication system. The teams had between 1 and 3 people in them. For those with 3,

they could nominate a Scrum master. However this designation proved tricky as the Scrum masters were typically participants who had less technical skills. This meant that it was difficult for them to understand the tasks that the rest of the team internalized. It was therefore not possible for the Scrum masters to enforce the Scrum. Therefore, in reality it became more of an eXtreme programming pair programming approach supported by a third participant who was involved in documentation of the solution and reflection (P12).

The teams self-organised (P11) into three teams to support the material, design, tessellation and fabrication (numbering) systems. AX2 showed that whilst the extreme programming (a subset of agile development) concept 'pair programming' worked well, that 'Scrum managers' were less well received by the architecture students. The participants produced working systems (P7) although they struggled to link these systems together. This should be a focus in future workshops. The team performed well on adaptation to changing requirements and where able to significantly adapt the final design 'on the fly' in the final presentation in response to the developing requirements of the client (P2). The teams self-organized (P11) around motivated individuals (P5) were co-located (P6) collaborated closely (P4), maintained a constant, sustainable and fast pace (P8) to deliver design frequently (P3) that were valuable to the client (P1). Interestingly in this workshop some of the technical excellence was provided to the participants by the tutors, however we feel this is important as it means that the tutors are part of the team (P9).

5.3. AGILE X 3 (AX3)

The third Agile X workshop was hosted at UniSA in Adelaide, and was structured around the requirements and input of the clients (P1). This communication was facilitated with frequent prototypes and reports to the client (P3, P4). The 32 participants were divided into 10 teams that covered a number of design, fabrication and installation tasks including: checking the design against the Building Code of Australia (BCA); production of the single coordination drawing; Structural analysis; Fire safety; drawings for landlord approval; arranging the cutting sheets for CNC milling; Painting; 1:6 Prototype production; and finally 2 groups focused on producing instructions for the construction sequence. In the first of the 2 weeks of AX3 we fabricated and assembled the structure based on the design from AX2.

Two significant changes that were made included a change to height of the pavilion and a change to the materiality of half of the pavilion during fabrication due to a late merging issue on site (P2). In the second week participants designed the panels that would infill the structure and assembled and installed the final pavilion. This process required a lot of coordination and collaboration which was difficult due to the distributed locations of the workshop (stretched between the digital and physical workshops). That said the experience, expert advice and support of the physical workshop staff were invaluable to the production of the prototypes and the fabrication of the pavilion (P9). There were a number of key features that defined the workshop including: an insistence that we only have one drawing, and that that drawing is correct.



Figure 4. Many hands: Fabricating the Agile X pavilion (Photo credit: authors).

In this way the participants were able to maximize the amount of work not done (P10), although the large number of participants meant that there was inevitably some redundancy in tasks, which should be addressed in future workshops. All participants reflected on their experience and performance in daily blogs and journals, some of these reflections include comment on improving efficiencies in the process (P12).

Table 1. Comparison of each workshops performance against the 12 principles of Agile Development.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
AX1	-		-	✓	✓	-	-	✓	-			-
AX2	✓	✓✓	✓	✓	✓	✓	✓	✓	✓	-	✓✓	-
AX3	✓	✓✓	✓	✓	✓	-	-	-	✓	✓		✓

6. Agile Design Principles for Architecture

P1 seems to apply more in the second and third workshops, this was mainly because there was no explicit client in the first workshop. This also meant that P4 (facilitate, client designer collaboration) was not possible in the first workshop. P2 and P3 similarly only applied in the second and third workshops. These principles were explored in these workshops because the requirements changed as the brief developed with the client. Interestingly the teams did 'produce working designs frequently' even though the requirements changed frequently in these last two workshops. P5 was not affected by the lack of a client in the first workshop. The first and second workshops both had large numbers and it appears that P6

was easier to achieve in smaller teams. A future recommendation would be for workshops to be housed in either the same space or spaces that are very close together. P7 needs to be addressed in future workshops. P8 is important not only to the success of the project but the health of the team and is a relevant principle for architectural design.

P9 reflects the professional basis of architecture. Whilst this is relatively simple to impose in a waterfall model it requires further consideration in an agile model. P10 was very helpful in the third workshop once we had explored the opportunity space in the first and second workshops. P11 happened organically in the second workshop. In the third workshop, the teams self-selected their partners but the tasks were prescribed, it might have been better for them to discover the tasks that needed to be done themselves. P12 (reflection) is an essential part of any design process but even more so in an educational context. This was supported in the third workshop by participants writing a daily reflective journal / blog that formed part of the assessment.

Reflecting on the 3 workshops above it seems that the agile principles are relevant to architecture. The second workshop most clearly represented the principle of Agile Development. The first workshop represented the least number of agile principles. The workshops showed that parametrics alone intensify some of the paradoxes of project management. This problem is compounded by the way that parametric systems are frequently developed in ad hoc approaches that do not follow development methodologies from computer science. Therefore, this paper proposes an approach wherein parametric systems are developed using agile development principles. The 12 principles can be quite specific to software and we therefore propose the following 7 adaptions: Agile design principles for architecture.

1. **Maintain a constant sustainable pace (avoid burn out).** It is necessary to take frequent breaks and adjust project constraints and load if required in order to maintain the health of the team.
2. **Encourage face-to-face conversation and colocation wherever possible and facilitate close, daily cooperation between stakeholders and designers**. Barriers to collaboration and communication should be reduced.
3. **Build projects around motivated individuals, trust and support them to self organize.** Encourage and support flat hierarchies where in tutors and participants are on the same team - learning and solving problems together. The flat hierarchy means that any participant can suggest changes to both the design work and the facilitation of the workshop at any point.
4. **Satisfy clients by early and continuous and frequent delivery of valuable designs.** An aim for agile design systems for architecture is to have parallel systems and that we can meaningfully involve the client early in the design process. Agile focusses on using technology to support collaboration with clients. In this way it is the collaboration and the constant testing and exploration of the design tools that enable the design to progress.
5. **Maximise the amount of work not done and measure progress on working interoperable design systems.** This does not mean that everyone needs to be an expert, but some do. This should not be confused with reducing the exploration

of the opportunity space, but focus on minimizing redundancy in the exploration.

6. **Welcome changing requirements, even in late development.** Close collaboration with the clients is not sustainable without high value design solutions to offer. To support this, it is important that the design systems are not only interoperable but can be reconfigured to support alternative design systems.
7. **Focus on technical excellence and good design whilst reflecting continuously on how to become more effective and adjust behaviour accordingly.** This provides an opportunity to capture and reuse valuable design tools and processes to extend exploration of the opportunity space and focus on how to do things better next time.

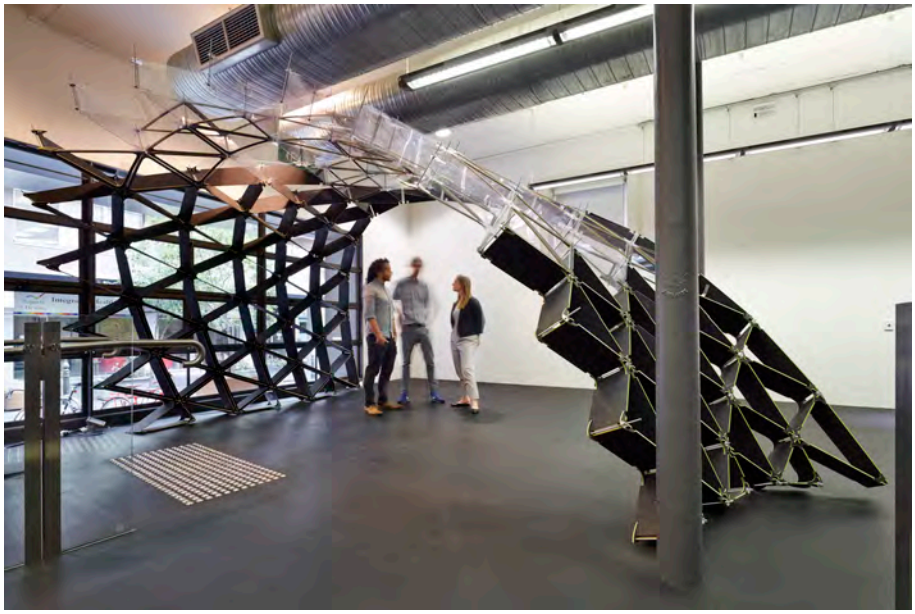


Figure 5. The final pavilion following the installation in the 3rd workshop (photo credit: Sam Noonan).

7. Conclusion

This paper argues that the underlying cause of many of the intertwined paradoxes presented in (figure 1) is the compression of the opportunity space into the front end of the project. Therefore, from the experience of a series of 3 workshops it appears that the expansion of opportunity space provided by the hybrid agile parametric approach presented here would relieve the compounding impact of the central paradoxes of project management. Expanding Droste (2010), this paper adapts the original principles of agile development to describe 7 agile principles for an architectural design. The potential innovation offered by the hybrid agile parametric approach is to expand the opportunity space offered in traditional approaches (figure 1), which has been observed based on the current preliminary

findings. Further testing in future workshops will be done in order to further verify the effectiveness and explore the potential, in order to critically theorize the approach for wider applications.

Acknowledgements

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CHALLENGES TO THE ADOPTION OF BIM IN THE CHINESE AEC INDUSTRIES

An Extended BIM Adoption Model

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Abstract. Despite strong encouragement by government guidelines and promoting efforts by the software industry, BIM is adopted at relatively slow speeds in construction industries across the world. The study presented in this paper examines the challenges to BIM adoption faced in particular in the Chinese construction industry across architecture, engineering and construction. We review recent literature addressing BIM adoption, develop a critique of common approaches to BIM adoption, and then propose our own, extended model to describe and assess BIM adoption processes. To demonstrate the model's suitability to evaluate temporal and collaborative dimensions during BIM adoption processes, we present results from a detailed survey we conducted among Chinese AEC professionals based on the extended model of BIM adoption and discuss how current Chinese BIM adoption in practice diverges from overseas BIM adoption strategies.

Keywords. BIM; Chinese construction practice; BIM workflow; cross-disciplinary collaboration; AEC.

1. Introduction

Building Information Management (BIM) is an umbrella term describing production and management processes in which construction procedures as well as physical and functional characteristics of buildings are represented digitally before they are committed to physical space and usage. BIM is typically employed to predict and control construction procedures and building performance with the aim of minimising cost in terms of energy, materials, and labour. Digital modelling provides several benefits to this end, including paperless editing and versioning, the possibility to provide current standard libraries of architectural elements and their attributes such as physical properties, cost and life spans, automated checking of conformity with some building codes and regulations, as well as networking and centralised data-bases allowing collaboration within and across companies

and industries. BIM promises significant savings across various aspects of design, construction, maintenance, and removal/reuse, while its adoption also represents a significant challenge to industry in terms of necessary investment into both skills and technology. The tension between these promoting and inhibiting forces are particularly strong in the Chinese context, where development and construction activities continue to overshadow those of other countries, while much day to day work is conducted at low skill and basic technology levels. Besides software industries marketing BIM tools, the government has emerged as a major force promoting BIM adoption in China recently, with a guideline by the Ministry of housing and Urban-Rural Development aiming ambitiously for a national BIM adoption rate of 90% by the year 2020 (MOHURD 2015, p. 3). This figure is left open to interpretation, with regards to, for example, the threshold beyond which a project or a building might be considered BIM-based, the entirety to which this proportional measure refers, or how the remaining 10% are expected to break down be-tween incomplete BIM adoption and projects to which BIM may be deemed inapplicable.

2. Brief Literature Review

Besides the promotion of BIM benefits, barriers to BIM adoption and recommended recommendations have been published in related literature, such as GCCG (2011, pp. 5ff.). BIM adoption models such as the BIM Maturity Model, also known as "BIM Wedge" by Mark Bew and Mervyn Richards (2011, p. 16.) and the Point of Adoption Model (Succar & Kassem 2016, p. 7) have been proposed to assess and to promote BIM adoption. Authors in the field continue to report not only on BIM benefits, but also on persisting barriers to BIM adoption. Lindblad (2013) offers an extensive list of BIM benefits (i.e. factors in support of BIM adoption), including efficiency of handling project or building related information, streamlined construction processes, productivity increase, economic and environmental benefits including cost reductions, improved product quality, improved building sustainability, improved time management, more convenient data exchange, improved customer/client communications, faster analyses, less data input and transfer errors, enablement of collaborations, and improved building performance. Lindblad (2013) also offers an extensive list of barriers for BIM adoption including slow technology development, limited compatibility and interoperability, difficulties of capturing fragmented AEC industries in BIM, difficulties to apply BIM across the entire design process and building life cycle, limited libraries of standard objects, high demands on computing hardware, the emergence of new professional roles and relationships in the context of BIM, the lack of international standards, difficulties of using BIM models for unintended purposes, lack of interest in the part of professionals working with well-established non-BIM procedures, time and cost required for training, limited confidence in data security, as well as challenges of agreeing on model ownership, on project responsibilities, on access rights, on intellectual property rights, on contractual responsibilities for inaccuracies, and payment arrangements. Eadie et al. (2015) further list the enabling of e-procurement and pressure from government clients as drivers of BIM adoption, while they list as barriers the absence of fee structures for BIM-specific services, limited training literature, and the possible reluctance of specialists to engage with

holistic planning approaches. Further barriers mentioned in existing literature are the necessary capital for investment into BIM adoption in particular for small practices, lack of case studies and samples, limited availability of BIM-ready collaborative partners, habits of 2D-based work, limited higher education BIM training, and a lack of BIM-ready samples for contractual documents (von Both 2012); the need for building proprietors to hire their own BIM teams to harness the benefits of BIM across the entire building life cycle and limited short-term benefits of BIM (He 2014); lack of mature policies and standards pertaining to BIM, uneven developments across different professions (Gu & London 2010), and a lack of BIM software adapted to local circumstances (MOHURD 2015). Several authors mention the limited availability of BIM specialists/managers as an obstacle to BIM adoption.

3. The Proposed Extended BIM Adoption Model

We note that current BIM adoption models do neither allow for the differentiated assessment of different building lifecycle stages, nor do they allow a differentiated quantitative assessment of the degree of adoption. The "BIM Wedge" by Bew and Richards (2011, p. 16.), for example, is in effect merely a one-dimensional four-point scale to measure quality rather than degree of adoption). Capturing these additional dimensions seems advisable for various reasons, most importantly the fact that degree of adoption and extent of adoption along building lifecycles (and hence across AEC professions) is necessary to assess consistency of BIM adoption, a key requirement to harness benefits of BIM adoption. To this end, we propose an extended model for the evaluation and visualisation of BIM adoption, which accommodates the "BIM Wedge" by Bew and Richards (GCCG 2011, p. 16) along one axis, building lifecycle stages along the second axis, and a dimension for quantification along the third axis (figure 1).

4. A Survey of BIM Adoption in Chinese Construction Practice

With a view to substantiating the extended BIM adoption model outlined above, we conducted an in-depth survey with BIM practitioners in China, drawn equally from architecture, engineering and construction (AEC) professions. The survey aimed to seek answers to the following core questions:

- Do overseas models of BIM adoption and use apply to contemporary Chinese A/E/C practice?
- How do Chinese companies adopt BIM in actual practice?
- Does BIM adoption lead to closer cross-disciplinary collaboration and integration?

As Chinese A/E/C firms are likely to be driven to officially report BIM adoption successes to comply with government guidelines, motivations of actual BIM adoption processes in China may differ not only from those publicly reported, but also from those assumed in overseas BIM adoption models. Local Chinese construction practice can differ substantially from overseas practice, which requires a more differentiated view on BIM adoption.

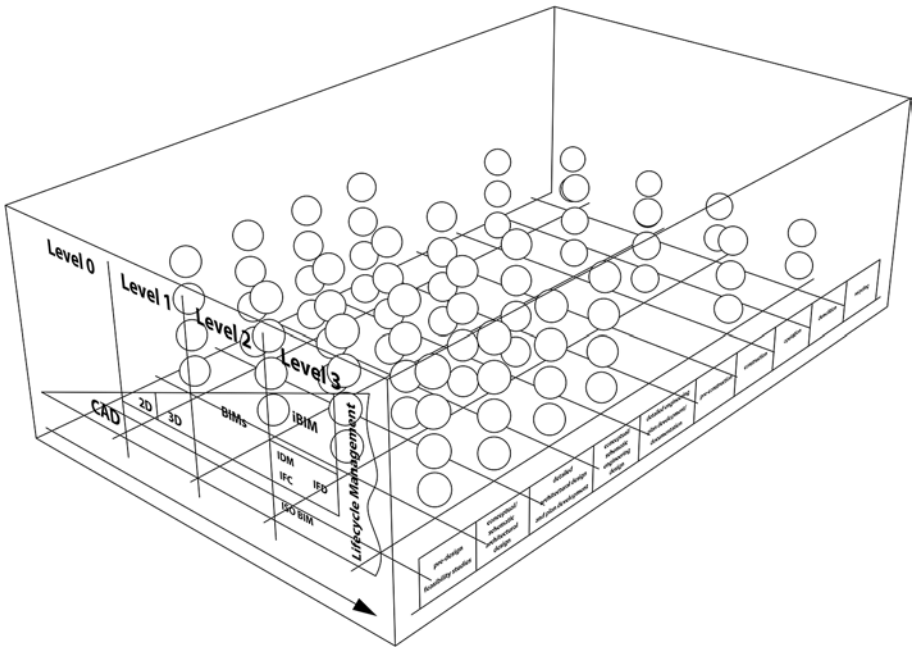


Figure 1. The proposed extended BIM adoption model accommodates the "BIM Wedge" by Bew and Richards (GCCG, 2011, p. 16) along one axis, building lifecycle stages along the second axis, and a dimension for quantification along the third axis.

Most Chinese design and construction processes are highly linearised, and professional separation is common. Most construction processes rely on 2D drawings to cope with demands for high-speed design and construction imposed by clients. While many firms report advanced BIM adoption rates, it is unclear whether BIM adoption is understood according to the widely accepted BIM adoption model developed by Bew and Richards for the GCCG (2011, p.16), or as requiring changes in existing professional relationships (Holzer 2016, p. 13).

For the study reported here, we focused on an in-depth survey of 13 AEC practitioners working in firms in the Shanghai / Suzhou region. Construction industry in this region is among the most technologically advanced in China and can be taken as representative of current advanced BIM adoption processes in the country. Survey participants were all drawn from companies that provide BIM services to their clients, with participants often occupying key roles in their firm's adoption of BIM. We found that all suitable participants worked in medium- to large-scale Local Design Institutes or construction firms. Smaller firms do not yet seem to adopt BIM technology or BIM-supported workflows. While the survey does not capture types of software used, it may be worth mentioning that the vast majority of BIM models currently constructed in the Chinese A/E/C professions use Revit as a common platform.

The study was planned and executed with the help of three undergraduate architecture students of XJTLU over the summer of 2016. The survey questions were

developed based on the literature review and the theoretical model presented in the previous sections. The survey was provided in a bilingual English and Chinese version, but administered mostly in Chinese language. It comprised a catalogue of 146 questions, structured into main three parts: First, a set of questions examining BIM adoption during different stages of the design and construction process; second, a set of questions relating to observations of BIM adoption reported in overseas studies, answered on a Likert scale; and third, open-ended questions to be answered during a brief semi-structured interview.

5. Analysis of Survey Results

5.1. BIM ADOPTION DURING DIFFERENT STAGES OF THE DESIGN AND CONSTRUCTION PROCESS

Analysis of the collected survey data confirmed that, besides some advanced high profile projects, most Chinese design and construction processes are highly linearized and characterized by a separation of professions. Most surveyed AEC professionals describe their profession's typical workflow as predominantly linear, with limited temporal overlaps of architecture and engineering process stages. This is even the case for professionals working in large design institutes, where different professions work in close physical proximity to each other. Figure 2 illustrates BIM adoption of Chinese design and construction firms based on the self-assessment of surveyed A/E/C professionals in the typical stages of the Chinese design and construction pro-cess (x axis), in relation to levels of BIM maturity (y axis). Deeper shades of colour indicate similar answers from several survey participants. The levels of BIM adoption are defined as follows: 0 = computer drawings, communicated on paper; 1 = computer drawings and models, communicated digitally; 2 = computer drawings and models communicated digitally, enhanced for decision support; 3 = computer drawings and models enhanced for decision support, communicated digitally via a centralised data hub. The graph remains identical to the x axis if no BIM use is indicated.

Based on surveyed professionals' self-assessment, BIM is reported as widely adopted at a relatively high level throughout the design and construction process stages across the A/E/C industries in China. Different disciplines indicate varying levels of BIM adoption depending on their professional focus: Architecture and engineering professionals tend to adopt BIM earlier in the design and construction process, whereas construction professionals mainly adopt BIM for the construction drawing and construction phases. Overall, A/E/C professionals report a strong focus on BIM use in the construction drawing stage. Very few surveyed professionals indicate BIM use for the purpose of building maintenance. The survey data further shows that the vast majority of BIM services is provided in-house, with firms preferring to set up internal BIM departments rather than relying on external specialised BIM service providers.

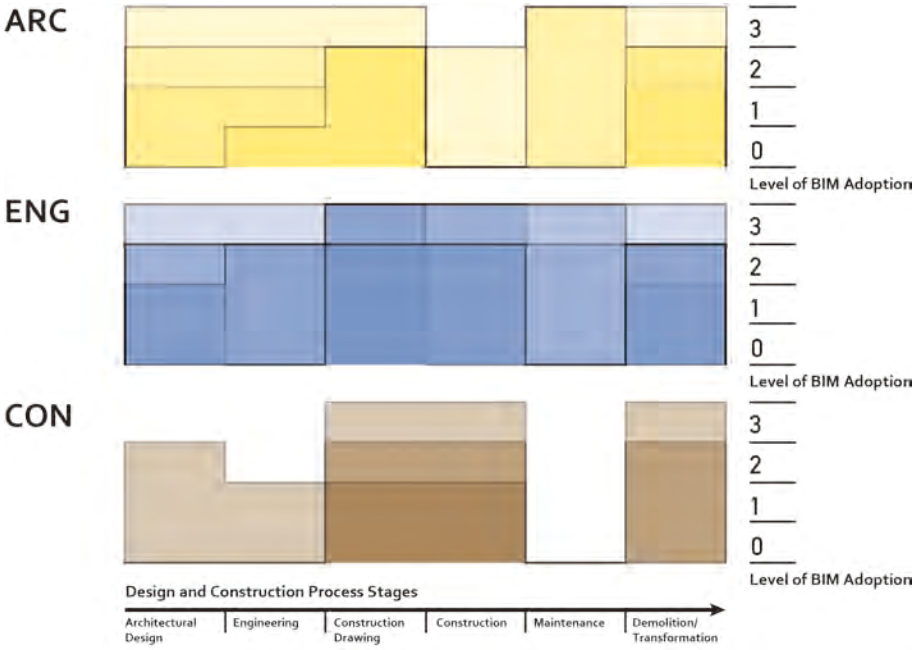


Figure 2. Self-reported BIM adoption during different stages of a design and construction process.

5.2. BIM ADOPTION IN CHINESE CONSTRUCTION PRACTICE COMPARED TO OVERSEAS STUDIES OF BIM ADOPTION

This section of the survey was based on questions answered on a seven point Likert scale. Survey participants tended to answer mostly within the central five-point range, avoiding the extremes of agreement and disagreement. Overall, results indicate a broad confirmation of overseas studies' results. Surveyed A/E/C professionals agreed that BIM adoption is strongly encour-aged through government guidelines and policies, while practical standards and guidelines are reported as not well developed. Legal implications of BIM and related contract documents are generally perceived as particularly unclear. Data collected in the open-ended interviews of the following survey section offered comparatively more and unexpected insights.

5.3. OPEN ENDED INTERVIEWS

The open-ended interviews provided a significant source of insight complementing and explaining results of the previous two sections of the survey. The two main questions asked in this section of the survey relate generally to factors motivating BIM adoption and factors discouraging BIM adoption. Survey participants typically offered additional opinions and observations relating to BIM in general. In this part of the survey, we noticed that most survey participants exclusively discussed their own discipline's needs and rarely mentioned coordination with

other disciplines' requirements and workflows. Most surveyed professionals do not seem to see BIM adoption as related to increased cross-disciplinary collaboration and workflow integration across the A/E/C professions.

Survey participants' responses indicate that core motivations for BIM adoption in the Chinese A/E/C professions are government guidelines and client requirements. Both architecture and engineering professionals reported that BIM capacity helps their firms to secure contracts with overseas clients, whereas many Chinese clients currently perceive BIM as an unnecessary cost item. Chinese clients tend to merely ask for provision of a BIM model without requesting its use during the design and construction process.

Most benefits from BIM adoption were reported by construction professionals, in particular for projects involving prefabrication. Architecture and engineering professionals had a more mixed perception of BIM adoption. Several architecture professionals described BIM models as an extension of 3D visualisations of the finished building, to show to the client to demonstrate the firm's competence and added value to the project. Architects further commented that time and effort invested into the construction of BIM models does not result in benefits to the work of their discipline, whereas construction professionals commented that BIM models inherited from architects are of little use for the purposes of construction and have to be re-built. Overall, improved quality of the built environment was not reported as a concern and motivator of BIM adoption, as "most buildings in China are regular buildings" that can be designed and constructed quickly and efficiently based on precedents.

Both engineering and construction professionals commented that 3D BIM models require more precision and detail, and thus time, for data input com-pared to previous practice, where 2D drawings left much to the construction firms to decide on site. Answers to the open-ended questions further indicate that actual use of BIM is mostly limited to discipline-specific models, with each discipline constructing specific BIM models. Survey participants commented that BIM models constructed by other disciplines contain too much irrelevant data that produces large and difficult to handle files.

A reported core factor discouraging BIM adoption in the Chinese design and construction process is that official contract relevant documents are currently limited to 2D drawings. BIM models are often required by clients but are not (yet) contract relevant. As a result, BIM models are typically not used for the purpose of supporting the design and construction process, but usually built only after the 2D drawings for the official contract documentation are almost finished. BIM thus becomes an add-on to an established design process operating primarily on the basis of 2D CAD drawings. Survey participants described this process as (literally translated from Chinese) "post-BIM" or "after-the-fact-BIM", the creation of BIM models only after relevant decision making processes have already concluded.

Generally, workflows employing BIM are perceived by most professionals as slow and inefficient - with the exception of service engineering where clash detection is seen as a main benefit. Only one survey participant mentioned use of BIM during the actual design process, in the case of a large-scale high profile project with an international client. In that case BIM was used (among other reasons)

to guarantee a high quality of construction and to prevent corruption on site by pre-defining each building in great detail.

6. Findings and Discussion: A New Perspective on BIM Adoption in China

While firms tend to officially present an official success story about BIM adoption and resulting opportunities in line with governmental guidelines, surveyed Chinese A/E/C professionals discussed both benefits and challenges of BIM adoption in their actual practice. We found that different participants of the same design process make varying assessments regarding the role and use of BIM in the same process. The survey indicates that BIM adoption in China focuses more on the presence of BIM models than on the workflows supported through such models. It is for example unclear how to interpret the Chinese government's call for 90% BIM adoption by 2020 - does this describe the mere presence of a BIM model or does it relate to a particular workflow? How can BIM adoption be measured?

With BIM still a novelty in the Chinese design and construction process (Zhang and Li 2013), work practices and processes have not yet been clarified or well established (Ding et al. 2014). While government guidelines push for widespread BIM adoption, many A/E/C professionals do not see a real need for or benefit in adopting BIM at this stage of development. Guidelines are seen as interfering with market-driven processes that emphasise speed and cost efficiency over integration and quality. To cope with these challenges, models of BIM adoption for the Chinese as well as overseas A/E/C industries do not yet seem to adequately consider factors relating to time and process. Chinese firms face excessively tight time constraints, which limit the scope of BIM adoption and the development of integrated and collaborative workflows.

Results of the study show that the presence of BIM models is not indicative of actual BIM adoption, as most surveyed companies produce BIM models only as add-ons to existing processes (described as "after-the-fact BIM" by several surveyed professionals). Similar to overseas studies, survey results indicate that new contract models are needed to truly establish BIM models as exchange platforms between different professions. This lack is a core challenge for Chinese companies aiming to adopt BIM.

7. Summary

In this paper we proposed an extended BIM adoption model, which allows for the differentiated assessment of BIM adoption during different building lifecycle stages, as well as the differentiated quantitative assessment of the degree of BIM adoption. We argue that capturing degree of adoption and extent of adoption along building lifecycles (and hence across AEC professions) is necessary to assess consistency of BIM adoption, which is a key requirement to harness benefits on BIM adoption. To substantiate the applicability of the extended BIM adoption model we presented an industry survey from China. Analysis of collected data confirmed that, besides some advanced high profile projects, most Chinese design and construction processes are highly linearized and characterized by a separation of professions, with each AEC profession constructing proprietary BIM models,

typically only after the actual design process has already been completed. Chinese AEC professionals continue to rely on simplified 2D drawings to cope with high speed demands common in Chinese AEC practice. Despite most firms' official claim to advanced BIM adoption, only few AEC professionals reported actual benefits from their company's adoption of BIM, and implied a limited scope of BIM adoption. Among those reporting benefits from BIM adoption are architecture and engineering firms working closely with overseas clients, construction firms employing BIM for enhancing management of construction processes, or firms utilizing BIM in relation to construction projects involving prefabrication - a practice that is still rare in China. Cross-disciplinary collaboration supported through BIM remains limited across the Chinese AEC industry. As the scope of this paper is limited, we will develop the project further in future, detailing the extended BIM adoption model as well as addressing specifically potential suggestions for Chinese AEC industries' BIM adoption strategies as part of embracing more holistic workflows.

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BIM AND PUBLIC ADMINISTRATION

The Brazilian Case

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Abstract. Brazilian construction industry's efficiency level is very low. Within the public administration sectors responsible for the construction of public facilities, this fact is amplified by the very nature of the laws regulating the public expenditures. Transparency and active public accountability are in its initial stages, creating misinformation and opportunities to corruption. Some public initiatives of adopting BIM (Building Information Model) for public construction projects are however taking place, seeking to revert this scenario. Corruption is one of the particular problems that are to be addressed for a efficient adoption of BIM in the public sectors. In addition to the traditional corruption-fighting tools, if we comprehend all the actors and processes that lead to the construction and operation of a public building as a whole complex system, where BIM is responsible for transparent flux of information, it can provide another layer of transparency, accountability and social control over the process.

Keywords. BIM; Public administration; Brazil.

1. Introduction

This article is a result of a research work currently undergoing at Nomads.usp Center for Interactive Living Studies at the Institute of Architecture and Urbanism of the University of Sao Paulo (IAU-USP), a Brazilian public university, and aims at establishing the theoretical and conceptual basis for the study of the possible impact of the introduction of BIM (Building Information Model) within the Brazilian context of public works, exploring the necessary changes in the workflow, new

information inputs and the limits associated with such new design processes.To illustrate this, this article is divided in three sections: The first section will paint a broad picture of the actual processes of public contracting in Brazil, dealing with the legal and practical aspects that guide public expenditure in buildings projects, and the role that is played by corruption in the processes. The second section deals with BIM itself, its concepts, its reach and shortcomings. We will present BIM as part of a complex system, capable of maintaining a coherent and transparent flow of information. The third section will deal with recent BIM implementation initiatives in Brazil in some sectors of the State' structures, establishing relations among proposed implementations exploring their limits and roles in changing the building process, concluding with some directions to new research works being developed by the Nomads.usp group aiming to verify and validate the possibly impacts and methods of BIM implementation on the given context.

2. Brazilian Public Works Context

Brazilian construction industry in general has a very poor historic of efficiency. Resources and materials waste due to deficient planning, low standardization level and non-rationalized construction techniques lead to overpriced buildings and recurring schedule delays (Baldry 1998). Within the public administration sectors, this figure is amplified by the very nature of the laws regulating public expenditures. Brazil's public contracts are mostly ruled by two legal frameworks: the 8.666/93 act, which deals with "Rules for public biddings and contracts", and 10.520/02 act, dealing with public auctions for more common expenditures, such as consumables and easily quantified objects.

The former is responsible for the majority of the public buildings bidding processes. In its text, the law defines what is called "the basic project": an intermediate phase between what is defined by the American Institute of Architects (AIA) as the "design development" phase and the "construction document" phase (AIA 2007). The law adopts a loose definition to the term:

"IX- Basic Project: a set of necessary and sufficient elements, with an adequate level of precision, to characterize the work or service or complex of works or services that are the object of the bid, based on the indications of the preliminary technical studies, that ensure technical feasibility and adequate treatment of the environmental impact of the undertaking, and that allows the evaluation of the cost of the work and the definition of the methods and the execution period, and should contain the following elements: (...)" (Brasil 1993, our translation)

In the text of the law, this definition is not tied to the Brazilian Association of Technical Normatives (ABNT in portuguese) committee definition of building design phases, and is open to interpretation of what is "sufficient" or "adequate".

One of the practical result of that lack of normative enforcement is that little time and few specialized human resources (architects, engineers, technicians) are allocated to the planning phase by public services, generating a great deal of improvisation and modifications during the construction phase. It is not unusual that either the initial cost arises without adding quality to the project scope or this latter is reduced for the same initial price (Rasmussen 2013).

As a consequence of this grade of uncertainty, the law permits, in its text, that new buildings are allowed to a 25% cost increase or decrease, and in the case of a refurbishment, this amount goes up to 50% of the original cost. In fact, the contractor cannot even object to this amendments to the original contracts. As the laws says:

"§ 1o The contractor is obliged to accept, in the same contractual conditions, the additions or suppressions made in the works, services or purchases, up to 25% (twenty five percent) of the updated initial value of the contract, and, in the particular case of building or equipment renovation, up to the limit of 50% (fifty percent) for their additions." (Brazil 1993, our translation)

This grade of uncertainty create improvisations on the construction site and costs and deadlines overruns. Santos et al. (2015), after an extensive comparative study of public buildings' construction process, ascertain that in the majority of cases these flaws are not there by mere chance, but are an intentional part of the bidding and building processes. The authors also note in their study that the responsibility for these uncertainty is the lack of well defined and precise preliminary studies and projects. This leads to another important facet of public contracts in Brazil: they are notoriously plagued by corruption schemes. Corruption isn't a mere question of enforcing a legislation or punishing the involved parts; it is a social problem as well as legal one (Filgueiras 2011). Corruption on public buildings contracts is an important factor in the Brazilian context, and some discussion of its concepts are necessary.

The very concept of corruption is based upon a shared secret between the involved parts (Abramo 2005). Another important concept about corruption, and specially important for this study, is that corruption is a wicked problem, one that is not easily delimited and is amorphous by nature, adapting itself to the attempts to curb it (Sabet 2012). It means that not only it is very difficult to identify and understand the actual mechanisms of corruption on a given context, but also that while attempting to combat it one cannot do so by half measures or with palliative efforts, as it will adapt itself to the new parameters (Sabet 2012).

Thus, it is not possible to discount official measures to deal with corruption; in fact, in the very core of these efforts, the strengthening of the State's structures and regulations are paramount, granting transparency of its acts (thus attacking the very concept of "secret" common to all corrupt acts) and accountability of public officials (dealing with the sequester of the State's structure by them).

In short, the perception of corruption is more attained to a shroud of secrecy in the State's acts and to the lack of access to the State's services and goods, as corruption acts in the border of the public and private, blurring and mixing this two concepts which are structural for the democratic States. In this context, corruption can be understood as a lack of inclusion of the population on the democracy system (Warren 2015).

Public services are intimately linked to public buildings or places. In Brazil, a series of nationwide spontaneous protests in 2013 had no clear agenda besides the dissatisfaction with the public services and officials. These demands lead to a "positive agenda" by the politicians at the moment, but those proved, about a

year later, to be insufficient to deal with "alarming levels of corruption in Brazil" (DeSanctis 2015, p. 394). The ongoing so called "Lava-Jato" (Car Wash) investigation that began in 2014 (leaving aside all its internal contradictions and doubts about its political uses), exposed a network of inappropriate relationships between Brazil's biggest construction companies and high-ranking political officials, all the way to the top of the government. The "Lava Jato" generated other investigations branched from the first, based on the successive leniency accords made by the involved companies and individuals.

Although the newspapers stamp the corruption linked to bigger projects, the problem is pervasive on all scale of public buildings construction (Santos 2015). Add to this scenario a characteristic lack of transparency in the government acts that only recently is being addressed by means of initiatives of electronic governance and accountability laws and processes (Article 19 2014) and we can infer that these two factors - the gaps in the legislation and the lack of transparency on the government acts - although aren't the only issues that contribute to the actual state of the public construction projects in Brazil, are in the root of the perception of lack of accountability and incapability of a broader social control that would otherwise contribute to minimize the problems detected.

Some public initiatives of adopting BIM for public construction projects are taking place, seeking to revert this scenario of waste and corruption. It is important however to conceptualize some points about BIM and its implementation on other contexts to compare with the Brazilian scenario.

3. BIM Concepts and Adoption Cases

In the context of this research, BIM is understood as a complete and differentiated information system, capable of influencing not only the project design and execution cycle, but also allowing greater technical and social control over public spending. If the processes, actors and variables that dictates the conception, construction and lifecycle of a public building are by their very nature diverse and complex, the problems detected are of the same nature. BIM here is understood as a part of a complex system, as defined by Ludwig von Bertalanfy. The author writes that a system is "(...) a complex of interacting elements" (Bertalanffy 1977, p. 84). The system can not be studied from the reduction to its constituent parts, under the risk of what Edgar Morin (1977) calls "decomposition" of it. However, even if the constituents of the system are not isolated, they must not be ignored. It isn't a focus on the whole to the detriment of the parts. This concept is important as to put in perspective that BIM isn't just a technological increment over CAD; its implications are more profound and demand a more holistic understanding of the whole context.

Manzione (2013) identifies the concept of a project as a flux of information, able to reduce the waste of time spent on information management. This concept can be "adopted for the design process, (...) allowing flexibility and coordination of different information flows and the interaction of the design process with the supply process and the execution of the work" (Manzione 2013, p.22, our translation).

In this methodology, the driver of the design process is the information itself, not the individual product of each task, and for maximum efficiency, it must flow unimpeded and integrated, a task that BIM systems can perform. (Eckert et al. 2001 apud Manzione 2013, our translation).

BIM, therefore, allows people to virtually experience a building, in all its aspects (Underwood & Isikdag 2010). This includes the design and construction process as a whole. Sacks (2012) informs that BIM is more than a technical exercise: it is a social exercise, focused on collaboration and cooperation, helping the decision making of the professionals involved by aggregating the available data.

Eastman et al. (2008) emphasize the importance of BIM as a form of production, analysis and, important in the case of the present research, communication of building models. Thus, BIM assumes the facet of a tool of production, management and organization of the information about a building. It is more than simply using another project tool, it is about an information system that can integrate with other systems, generating and receiving information. These concepts tie in with the definition of a system in the aforementioned von Bartalanffy's text.

But even as this complex view allow for a holistic vision of the processes involved, it also results in a slow rate of adoption of this concept. There are several studies on the implementation of these systems, comparing the moment of transition from hand drawings to CAD (Computer Aided Design) platforms, and the difficult task of modifying processes and procedures that are already ingrained in design. Leonardo Manzione (2013) after a complete bibliographical review detects that still, within the construction industry:

"In general, (the) culture and the mentality of 'knowledge silos' prevail in AEC (Architecture, Engineering and Construction), and the exchanges based on documents between professionals and the production chain occur in an uncoordinated and low intelligence manner. Decisions are often taken autonomously and without multidisciplinary participation, and with the absence of accurate holistic understanding" (Manzione 2013, p. 9, our translation)

The author, in his thesis, points out that despite a relative profusion of works on the subject and a general interest in the technology, publications generally adopt a "messianic" tone, more interested in offering BIM as a "product" to be sold to the companies than a complete system that requires an overall restructuring of the design methods and concepts (Manzione 2013).

Therefore, an important role is played by the public sector. As Succar (2009) puts it, the public sector is a policy-maker actor, and thus helps to create the foundation, to regulate and to oversee this process. In Brazil it also overlaps, in a smaller scale, with the Process field actors (as defined by Succar 2009), demanding and sometimes producing projects and buildings. Thus, it is understandable that public building and contracting processes are important to define long-term policies and developments, and to implement BIM in a complete, and not fragmented, way.

For instance, Cheng and Lu (2015) in their very extensive study of worldwide BIM adoption identifies some countries or areas that are currently adopting and creating standards for BIM implementation. The authors also identifies six roles that the public sector play in the BIM adoption: Initiator and Driver, Regulator,

Educator, Funding Agency, Demonstrator, Researcher (Cheng & Lu 2015). Of special interest for this study, on all of them the role of Initiator and Driver was taken by the public sector, even if other roles were not attributed to it. According to the authors:

"Undoubtely the public sector plays a key role in initiating BIM. Public organizations in most countries has set their BIM goals and required the use of BIM in public construction projects when they first jumpstarted BIM technology (...)" (Cheng and Lu 2015, p. 466)

Wong et al. (2009), in their study of the role of major stakeholders in BIM implementation in various countries in the world, declare that:

"(...) It is observed that the support of the central government towards BIM implementation can be regarded as the driving force towards higher utilization of BIM in those countries. If the support is strong it would create a uniform environment for nation-wide acceptance of BIM. BIM requirement would then come under legal jurisdictions. (...)" (Wong et al. 2009, p. 6-7)

BIM implementation on virtually all aspects of the construction industry, as documented on the extensive works of Succar (2009) and Succar & Kassem (2015), is necessary to achieve its full potential, although that, by the relative novelty of the frameworks and technologies involved, there weren't enough time yet to a full implementation as preconized in these works. (Succar 2009)

One of the most successful cases of BIM implementations is the United Kingdom's, by the establishment of a "BIM Task Group" by the government, with a clear and objective roadmap and extensive interaction and collaboration with the private contractors and the academic community. Also in the works is the roadmap for BIM level 3 implementation, one that would fully realize the BIM framework in the entire lifecycle of an edification and and the "one-model" concept. The final objective is the called "Digital Built Britain", where the model acts as more than a one-way information repository, but allow that cloud computing, the internet of things and big data information to be used and incorporated to the model, reflecting the many levels of relationship beyond the pure physicality of the building. (BIS 2013)

This experience has the potential of expanding the BIM concept beyond the purely technological and industrial processes, opening up the possibility that information generated by external actors (physical, natural, social or otherwise) outside the building can be incorporated automatically to the model, helping the decision making progress in eventual refurbishments and expansions by providing and incorporating feedback in its entire life cycle. It can also generate a database of real-world scenarios to future buildings of that kind or placement, important in the case of public buildings that are, in the name of cost savings and lack of information, built in a serialized manner with a disregard of the local peculiarities. It can also expand the reach of the information about all processes involving a public contract to the public and professionals at large, who can then engage in a social control of the process.

4. Comparison and Guidelines

It is clear that the simple implementation of BIM isn't *per se* a solution for the construction issues of low quality, high cost, high uncertainty and associated corruption processes as described in the first section of this article. The literature about the concepts of BIM preview that the first phases of BIM adoption in a given context are fragmented by nature, and the full implementation of the system can only take places as a multi-actor driven effort. (Succar & Kassem 2015). As the international cases cited verifies, BIM adoption is generally driven by initiative of the government in conjunction with other sectors (Cheng and Lu 2015), even if in later stages of implementation and diffusion its role is diminished (Succar & Kassem 2015).

Brazil's adoption of BIM has been slow, with only private individuals and few fragmented public initiatives fully embracing it. As Kareem and Amorim (2015), in its comparison of the actual state of adoption of BIM in Brazil to six countries of the EU shows, some of these initiatives are very advanced, but with limited reach:

"In Brazil, although BIM is not mandated at any level, industry reports (...) shows that the use of BIM in Brazil is focussed more on cost control at the construction phase rather than on the collaboration with owners. This represents a reversed BIM usage pattern to the one witnessed in other countries (UK, France, US, Germany, etc.) where BIM entailed more collaboration with owners and other project stakeholders. This use of BIM and the maturity level of contractors in Brazil could trigger a middle-out type of implementation pressure across the supply chain. However, this effect could be limited or slow. Indeed, seminal research on innovation diffusion in construction industry demonstrated that coercive forces are more significant in influencing the extent of BIM adoption especially if they are mediated by the client or owner (Dimaggio & Powell 1983; Mitropoulos & Tatum 2000; Cao et al. 2014)" (Kareem 2016).

Worth mentioning is that the brazilian army's Diretoria de Obras Militares (Directorate of Military works) has implemented a system called OPUS. As Kareem reports:

"OPUS is an integrated system for the management of project delivery phases (e.g. procurement, design construction, demolition) that includes information about over 16.000 buildings making up the asset portfolio managed the Brazilian Army. OPUS is also a web-based system in which 2D and 3D models, from several sources and in several formats, can be overlaid on a Google map using a system of coordinates. Over the web, the system allows the switching over several levels of model details (3D, 2D, etc.) or by project delivery phase (e.g. construction, demolition, etc.)." (Kassem 2016)

The OPUS system represents an advanced technological infrastructure, which are in development in other countries. However, by its military nature, it is not publicly accessible, and by its limited reach, cannot be considered an extensive governmental policy.

In Brazil, an isolated implementation of BIM would produce results below the desired ones. Thanks to the wicked nature of corruption, the risk of sequester of the system by the *status quo* to maintain its dominance over the processes of

public works' planning and building is real. A transformation of the entire legal framework is necessary, including the establishment of procedures and standards by the public government. These transformations, however, are beyond the scope of this paper, but suffice to say that in the actual Brazilian moment, measures to address some issues of transparency and accountability are slowly being discussed or taking place (accountability law bills in the congress, the information access bill, etc.), creating an ideal moment to the implementation of BIM guidelines and policies.

Comprehending BIM as a system and a framework for information flow and concentration, its vital that it is incorporated as a central piece of these policies, as Kaseem and Amorin (2015) diagnosis in their extensive report. They recommend the creation of a working group composed not only of government officials but also the society and stakeholders of the area (general public, contractors big and small, the academy) at large. It must, however, be driven as a public initiative, for its effects must be generalized over the entire market. A public forum involving all areas would be adequate to breaking the historical power concentration on the executive branch of Brazilian government, accustomed to deliver policies in a top-down manner (Ríos-Figueroa 2013).

5. Conclusions

Implementation of a system as revolutionary and complex as BIM in a context even more complex as any given society is a daunting task, one that cannot be taken lightly or in an isolated manner, with decisions taking place at closed doors. In the special Brazilian case, some issues that the BIM hopes to address are not pure processual flaws; one can argue that are built-in in the system to produce opportunities of mismanagement of public money in the fringes of the actual uncertainty and opaqueness of public acts.

However, international experiences shows that BIM is effective in dealing with this shortcomings, when adopted in a sensible and customized way, dealing with the particularities of each context.

BIM also can be approached as a complex system, on that the different actors exchange information between them, giving and receiving inputs and feedbacks. In this context, BIM is not the system per se, but the responsible for the coherent and unimpeded flow of information, generating a global comprehension of the object being projected or built in a more attuned way.

This characteristic also echoes in the very basic concepts of good governance and social control: unbiased and depersonalized information control and transparency in the public acts and decisions.

Ultimately, this framework can be used not only to permit a passive control by the civil society of the decision making and operationalization of public works, but also incorporate public-driven feedback on these actions, via active channels (ombudsman offices and prosecutory departments, surveys) or passive data collection (big data, remote sensing via internet of things).

This would, in one hand, empower and involve the civil society in the political and governance systems; in the other hand, would exert pressure over public offi-

cials to keep in mind the collective interest over the particular, effectively reducing the power of public officials and holding them accountable for any misdeeds.

The academy, in this initial stage, has an important role of identifying the common and disparate elements of another experiences and contexts and create guidelines for the successful adoption of BIM, aiming for a more quality, productivity and social control of the process. Its not a streamlined or easy process; interfering in a possibly corrupt system, which tends to close itself to new actors outside their sphere of influence is a difficult matter, but one that the academy is fit to deal with.

As the principles of the scientific work are its transparency, openness and systematic review, the very act of studying some aspects of the problem is bound to attract attention and a greater scrutinization of the bidding/construction process. Academy also can put forward new proposals and methods, and validate it independently thru the scientific community, thus helping to break the aforementioned wickedness of the corrupt system. Without the safeguard of transparency and social engagement, any new method or technology could be incorporated in the corruption schemes, mantaining the *status quo*. Therefore, the academy is fundamental by injecting rigour and transparency in the implementation of new public building processes.

With these points in mind, the Nomads.usp group is tackling the matter in the Urban Cartographies project. The project is in its initial phases of development, and in one of its lines of research, aims to explore the parameters to be used in BIM based parametric design programs, in a cycle that sees its results being available to the studied communities, thus generating greater transparency and enabling social control and engagement over potential public decisions.

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REGIONAL BARRIERS

A Study on the Applicability of SHoP's Project Delivery Strategies to China's Architectural Environment

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Abstract. This paper discusses New York based architecture practice - SHoP's project delivery strategies, to demonstrate an avant-garde methodology in pursuing architect-led project environments where optimised outcomes are achieved with digital workflows. The paper elaborates on how today's Chinese architecture adopts global digital trends while certain barriers are impeding development of computationally integrated project delivery modes. Thirdly, the paper indicates the emergence of a new generation of digital architects in China, showcasing their practices to argue for the regional applicability of SHoP's working mode. The paper concludes by summarising the disadvantages of the current Chinese architectural system, advocating the necessity of a systematic digitalisation, and discussing the Western potential in China's modernising architecture.

Keywords. Chinese architecture; project delivery; digital paradigm; SHoP; digital workflow.

1. Introduction

In the West, technological developments are arguably keeping pace with ideological revolutions. Since Lynn's "architectural curvilinearity" broke the conventional logic grid of orthogonal representations and Gehry's multi-disciplinary materialisation strategies in non-standard forms, the Western architectural industry has been creating a digital environment for a wide range of potential results. In China, in contrast, the concept of "architect" was not even introduced as an independent profession until the 1920s when it replaced the traditional role "craftsman". Since then, the impact of Chinese architects decreased along with a reduction in liability. The booming urbanisation in major Chinese cities has fostered robust real-estate markets where domestic architects are accustomed to a profession of "producing

quantity" rather than "designing quality". Until now, the inertia of this rapid development shields Chinese architectural modernization from self-criticism. A monotonic project delivery (PD) mode remains sluggishly in responding to industrial informatization. To cope with these circumstances, Chinese architects have become "the most productive drafters" (Jiang 2005).

Arguing for the integration of Western trends in a Chinese environment, this paper presents New York based architecture practice SHoP as a case study of pioneers who advocate for a digitally integrated project delivery (IPD) mode that conveys new architectural complexities and computational representations. SHoP, founded in 1996, represents a generation of American architects that is redefining traditional "design-bid-build" (DBB) systems. More than in design tools only, computation is implanted in the firm's organisation, communication, and management, increasing flexibility as well as profitability from design. SHoP contains four businesses, among which the coherence of SHoP Architects (SA) and SHoP Construction (SC) reveals its PD philosophy of being a "digital master builder". SHoP eliminated tooling incompatibilities among multidisciplinary collaborations and centralised architect's authority in projects.

2. A SHoP Mode of Working

"SHoP is the kind of architecture firm that builds" (Nobel 2012). The firm is a digital avant-garde company who sees PD as communications and collaborations. It formalised a contemporary IPD methodology that included computation and was informed by manufacture industries. Neither the "hard-to-imagine" architecture from parametric enthusiasts nor the "hard-to-draw" sculptures by formalists, SHoP is pursuing the materialistic outcome of design value.

2.1. SHOP = SHOP ARCHITECTS (SA) + SHOP CONSTRUCTION (SC)

One of the criterion for SHoP to sustain a digital PD system is the architect's control over the project materialisation. Founded in 2007, SC bridges virtuality and reality; idealism and materialism. This agent provides engineering services in building rationalization and coordinates conversation between designers and makers/builders. With various professional backgrounds besides architecture including political science, engineering, marketing, real estate development, and art history, the five founding partners cognize SHoP's architecture through perspectives of philosophy, aesthetics, technology, finance, and administration (Nobel 2012). Through collaborating with software company Dassault Systèmes, SHoP brought managing software ENOVIA and engineering tool CATIA (Digital Project) on the Cloud, to create a holistic digital environment where schedules, building model, fabrication information and business requirements integrate. Therefore, the firm's precedence in digital technology provides the advantage of financial efficiency and simultaneously frees design explorations.

2.2. TECHNOLOGICAL STRATEGY

From the aviation industry, SA learned how a performance-driven taxonomy can be used to reduce design compromise. "Design optimisation" plus "direct fabrica-

tion" is the core strategy of his project materialisation. Project "A-Wall" (figure 1, left) is a showcase of this approach and consists of an irregularly curved surface engineered by 496 unique triangles, of which material utilisation and geometrical undulation have been maximally preserved. SHoP here established their philosophy of computationally balancing project rationality and performance, which was expanded in their later practices.

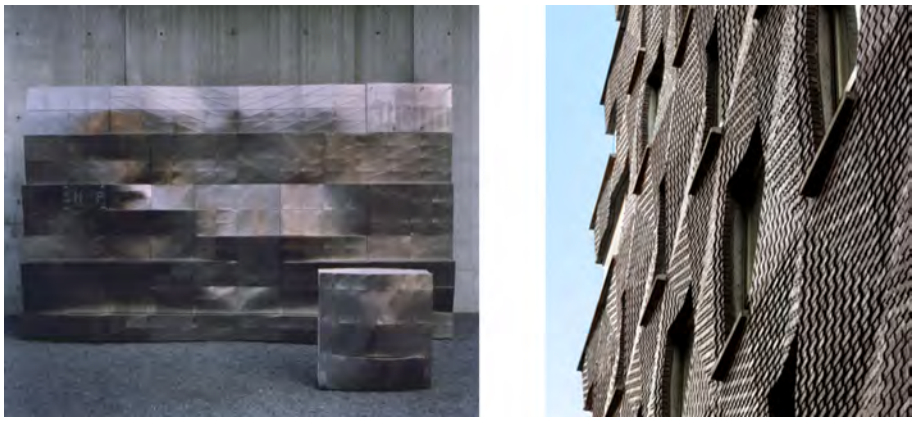


Figure 1. (left) "A-Wall"; (right) The facade of "290 Mulberry" (both taken from SHoP's website: http://www.shoparc.com, 2016).

The project "290 Mulberry" (figure 1, right) was a pilot project of the IPD mode (BIM). The building sits in a specific coding zone that requires masonry cladding on its north and west facades, and restricts ornamentation beyond the planes of the building envelope up to 10 percent of every 100 square feet. The project is a showcase of the firm's workflow in 1) constrains inputs; 2) design optimisation; 3) direct fabrication; and 4) quality management.

1. The input constraints include code regulations, material performances, and fabrication parameters. For example, besides aforementioned site rules, brick cantilevers are required to be within three-quarters of an inch to its neighbour for structural purposes (Moe 2008). Here, SHoP used GenerativeComponents (GC) to calculate design limitations before exporting the model to Digital Project and Autodesk Revit for detailed engineering. Early collaboration with fabricators and installers enabled the architects to achieve the maximum amount of projection for each undulating panel, while incorporating casting and shipping demands.
2. Design optimisation translates formal complexity into manufacturing simplicity. With information models, SHoP balances rational cost and aesthetic goals. In this case, Rhino and GC helped SA to maximise undulation varieties with the minimal amount of master molds and form liners (SHoP Architects 2009). Customised scripts were developed to control panel iterations in normal, corner, and window conditions (figure 2, left).
3. CNC fabrication guarantees the direct data feed from Digital Project - "direct fabrication". In "290 Mulberry", the early collaboration with the fabricator Architectural Polymers has tested the brick layout flexibility in mock-ups. Form liners

and master molds in optimised variations were cut out in rubber directly from SC's output (figure 2, middle), then embedded with bricks sequentially.

4. "Direct fabrication" eliminates errors from the miscoordination between design documents and shop drawings. The information model helps installers precisely locating each prefabricated component. Furthermore, key data related to financial, marketing, and scheduling plans is extracted for various team members, facilitating better communications with both administrators and clients.



Figure 2. (left) Façade panel variations; (middle) CNC milling form liner (both taken from Autodesk Gallery: http://www.autodesk.com/gallery/exhibits/archive/290-mulberry, 2016); (right) Cantilever of "The Porter House" (taken from SHoP's website: http://www.shoparc.com, 2016).

2.3. FINANCIAL STRATEGY - A "GAMBLE" FOR A "DREAM"

Interest hierarchies between client and architect are not always aligned. Architects often are requested to reduce design complexity or step back into a "safe zone" where his/her ambitions do not conflict with the investor's priorities. To bypass these "inevitable" limitations, SHoP links the firm's profit with the added-value it creates in a project. Through becoming the investing partner, SHoP aligns its financial interest with aesthetics pursuit. SHoP's subjective engagement with a project's financial structure and political discussion establishes its predominance in design delivery. Their strategical interpolations have revised the role of the modern architect and turned him into a digital master builder.

"The Porter House" is one example where SHoP engages in project finance. Here, the firm linked its service fee to the sale prices of the condominiums. Not only did they believe the added design value would increase sales prices, but receiving part of the project ownership freed the architect in design and ceased debates in concept generation. The proposal of "The Porter House" introduced a six-floor cantilever - an expensive proportion that most of the developers rejected (figure 2, right). With a holistic calculation in the digital environment, SHoP distributed technical cost accordingly. Cladding variations were minimised in the design, and the financially efficient zinc was used. Thus, a large funding portion was spent on formal innovation while the project still ended up with a secured profit.

3. Barriers in China

Chinese architecture has been following Western paradigms. More than seventy percent of first-generation architects who founded the "Architectural Society of China‘’ (the first Chinese architectural association) in 1927 were returnees (Jiang 2005). Additionally, in 1995, a Western trajectory-based national architectural system was established when the State Council released the "Detailed Rules for the Implementation of the Regulation of the People's Republic of China on Registered Architects‘’. A nation-wide "plan-design-bid-build‘’ PD mode was created since. In a sustainable economic growth, domestic architects are acting as interpreters of a national ambition to urbanise and maximise economy growth.

Chinese policy did facilitate the digital paradigm shift among industries. In 1992, the ninth "five-year plan" initiated "throw off drawing boards" - a national manifesto that encouraged industries to adopt the computer-aided software. Since then, both architectural practice and pedagogy have admitted two aspects of computation: the 2-dimesional representation of building sections and the 3-dimensional visualisation of model. CAD companies started booming and AutoCAD became the standard industry tool. The eleventh "five-year plan" "throw off paper drawings" has been promoted since 2006, aiming to fully integrate a "CAD to CAM" workflow. Yet, a rather "hands-off" mode of project development permits the architect to reduce financial risk, yet simultaneously traps him in a domain of conservative cognition in materialisation. Chinese modern architecture has built up an inflexible hierarchy to which domestic architects succumb. In this paradigm, limited progress has been made since the first manifesto was accomplished in the year 2000. Compared to the West, Chinese architecture is arguably responding sluggishly in this second phase for three reasons: 1) the dispersion of project authorities, 2) the architect's role and liability differences between China and the West, and 3) a weaker system integrity than that in manufacture industries.

3.1. CHINESE "ARCHITECT" = ARCHITECT + SUPERVISION ENGINEER

Historically, both the RIBA system (UK) and the AIA mode (USA) defined "the architect" as a professional who is authoritative in material selection, permit application, implementing consultancy, contract management, and general supervision (Jiang 2005). The Chinese system, however, removes more than half of the above. Unlike the tripartite Western PD organisations which include owners/clients, architects/engineers, and contractors, China introduced a unique fourth party: the "supervision engineer" (SE). Not only does this isolate the architect to a singular role of drawing, it also heavily cuts down the architect's profits. In 1996, the "Construction Law of the People's Republic of China" stipulated SE as a neutral fourth party that guarantees both the ethical and professional execution of work by engineers and contractors. Even though contractually he represents the client/owner in project rationalisation, paradoxically his role impedes an integrated workflow or complexity innovation because:

1. Disordered early-stage management: in concept generation, the segregation between SE and architect increases financial uncertainties. Undetermined materials, equipment, and techniques lead to pragmatic empiricism. As is often the case,

computational applications barely contribute to architectural ontology other than enlarging ornamental vocabulary. This authority dispersion results in SE nor architect being committed to the financial management or scheduling in an early-stage planning.

2. SE is a profession without expertise. The SE is neither an independent discipline in Chinese college education nor a technical ability developed from any systematic training. A third party not involved in the design of architects/engineers takes part in the project. His neutral status results in the lowest commitment to project completeness and does not enable providing technical support during construction. Solely supervising the translation accuracy of construction documents to on-site implementation, the Chinese SE has become a slave to intermediate products that encumber "CAD-CAM" integrity.
3. A low digital-threshold: the SE's liability ambiguity makes him a mixture of public administrator and a for profit organisation. His traditional managing approach requires low software competence and no compatibility with an integrated digital environment. The computation revolution aims to eliminate unnecessary interruptions in the workflow, thus directly challenging the SE's existence.

3.2. COMPARISONS WITH THE US SYSTEM

An architect-led project delivery (ALPD) inspires both ideological and technological evolution in the digital age. The evolution of the US system from the 1970s' "design-bid-build" (DBB) mode to the current "integrated project delivery" (IPD) (AIA 2012) is a process of architects gaining workflow autonomy. Given all-round responsibilities, US architects utilise digital power to precisely control progress and reduce risks while potentially increasing profit. The Chinese system, in contrast, continues the DBB mode, reducing the architect's profit due to his liability reduction. Financial criteria restrict digital power as a facilitator with which Chinese architects could potentially optimise their benefits from the current mode.

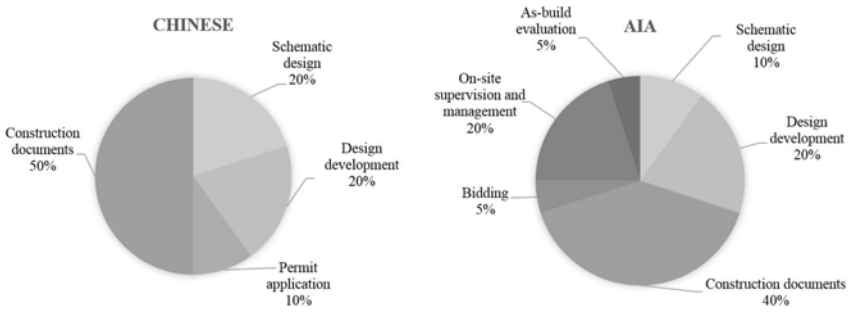


Figure 3. Diagram of the Architect's liability distribution in "design-bid-build" modes in the Chinese and AIA system.

The IPD mode of the AIA system emphasises the need for the architect's engagement with both the client/owner and contractors in the early stage to integrate accessible constructability and restrictions in conceptual design. Yet, Chinese ar-

chitects are only involved in the design-related discourses of the budget, time, and organisation. In other words, there are strong incentives to perform conservatively to survive in this lowest-cost competition. Furthermore, in the planning phase Chinese architects are not required either in 1) making construction plans, 2) optimising construction techniques, 3) supporting submitted documents, or 4) consulting contractual issues. In the meanwhile, during construction and use phases, they are removed from 1) oversighting on-site implementation; 2) supervising technical execution; 3) on-site design modification; and 4) evaluating as-build quality. Liability distribution (figure 3) has isolated Chinese "architects" into a single-functional discipline, impeding the development of a computation-aided IPD mode.

3.3. COMPARISON WITH MANUFACTURE INDUSTRIES

Since the 1940s, Western aviation, automobile, and high-tech industries have been endeavoring to achieve an intelligent integration of computational design and automated production. From Gehry Partners to Gramazio & Kohler, the architectural industry is catching up as well. Western pioneers are pursuing a business-industrial mode, where architectural autonomy equals objective productization and subjective personalization. Chinese manufacture industries have adapted this trend rapidly. For example, the Pearl River Delta (PRD) area has become the largest cluster of high-tech manufacturers and innovative business, where companies such as DJI (a drone manufacturer) and HUAWEI (a mobile manufacturer) have developed mature PD systems to establish their international competitiveness. Nevertheless, Chinese architecture comparatively lacks.

Firstly, the separation of stakeholders matters. Profits of manufacture industries are tied with project planning, design, production, and sales, as they invest in digital/technological innovation for long-term paybacks. Yet, unlike cars or cell phones whose appearance are as crucial as their functionality, Chinese architects are neither paid for building aesthetics nor for as-built qualities, but by project floor area charges or ratios. As they are only the author of the "design" - an added-value defended by architects but ignored (in most cases) by owners, architecture's investment remains limited in China. Secondly, the opportunity to invest in short-term labour-intensive activities is replaced by avoiding the financial risk of possible "unnecessary investments". Participants join the modern architectural activity through separated bidding, where imbalanced digital competence and incompatible software environments may compromise an architect's initial intent. As in above-mentioned circumstance, most large architectural corporations in China are using digital/BIM technology to accelerate the billing process while hiding in a conventional system.

4. The Applicability of SHoP's Strategies in a Chinese Environment

SHoP is evolving project delivery and management, inspiring change in the architect's role in an integrated digital environment. In China, developments in architecture behave differently. At the time when SHoP established its philosophy, the US's digital revolution had already been accepted both in terms of software and hardware. Along with the increasing cost of the labour force there, the dig-

ital paradigm shift encountered less socio-cultural obstacles than China did. On average, China's construction industry today is 15 years less-developed than Germany's architectural manufacturing business (Yuan and Ge 2011). As a population of 40 million remains in the construction industry, computational design software is spreading much faster than CNC manufacture. China's architecture requires regional adjustments when adopting the SHoP's mode of operation.

4.1. TECHNOLOGICAL ADJUSTMENT - "LOW-TECH" IMPLEMENTATION BY "HOME-GROWN" ARCHITECTS

"Home-grown" architects (Williams 2015) make up a new generation of returning Chinese practitioners who have been implementing modern Western ideology and methodology into the domestic market. Among them, a digital sub-group has started exploring regional expressions, integrating local productivities. Bridging the gap between computational design and fabrication, these avant-garde architects have adapted specific materialisation strategies. "Low-tech" implementation is one technological response to the applicability of the SHoP's "direct-fabrication": digital tools enable "home-grown" pioneers to increase formal complexity and output detailed information while making "changes" in the design optimisation to cope with a less-developed construction environment.

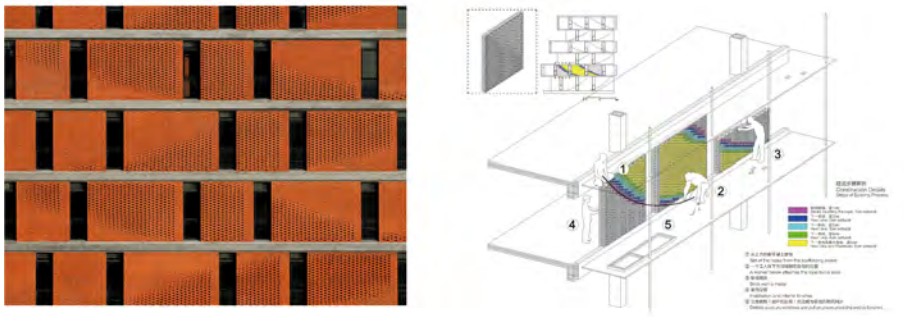


Figure 4. (left) Masonry façade of "Songjiang Art Campus"; (right) Brick setback iterations (both taken from Archi-Union's website: http://www.archi-union.com, 2016).

Among Chinese digital firms, Archi-Union is one of those succeeding in a regional integration between innovative exploration and building rationality. The firm is seeing computational power as an extension of existing material cognition and craftsmanship. In the "Songjiang Art Campus" (figure 4, left), "low-tech" strategies were applied to the gradient of a masonry façade. Compared to the "290 Mulberry" by SHoP, Archi-Union achieved a similar performance in ornamentation by digital tools including Rhino and Grasshopper. A fully manual implementation, in comparison, characterised a Chinese unique workflow mode. First, the "Flemish bond" was adopted which contains two headers between one stretcher. Through pushing bricks outside sequentially, architects achieved the pattern in the digital environment and labelled each setback for output. Then, however, the labourers encountered difficulties in construction. Not only the variations of brick

setback led to an uncontrollable inaccuracy: the continues gradient confused the bricklayers. Archi-Union then adjusted the script to match the on-site demands. Brick setbacks were reduced to 5 iterations and all the "headers" were fixed as a reference grid for "stretchers" (figure 4, right). In addition, contractors spontaneously invented customised tools such as wood indicators and ropes to assist implementation. With computational optimisation and "low-tech" adjustments, this project secured the financial efficiency and simultaneously represented the digital materiality of a traditional material.

China will remain a semi-digital construction environment for a long time in the current socio-economic environment. Like Archi-Union, digital pioneers such as Studio Pei-Zhu, HHDFUN, and Atelier cnS also experimented with non-standard practices including a "low-tech" philosophy. In the "Rizhao Public Bathroom" by HHDFUN (figure 5, left), architects simplified 3D curves into a combination of line segments and arcs (Wang 2012) to reduce fabrication complexity and improve implementing comprehensibility. Another example by Atelier cnS integrated the parametrically generated façade pattern with industrial modulization in the "Foshan Art Village" (figure 5, middle). To rationalise financial challenges in production, the firm considered regional productivity and panel installation techniques in the early-stage modelling phase.



Figure 5. (left) "Rizhao Public Bathroom" by HHDFUN (taken from HHDFUN's website: http://www.hhdfun.com, 2016); (middle) "Foshan Art Village" by Atelier cnS (taken from Atelier cnS's website: http://www.shoparc.com, 2016); (right) "Playroom" by Zhu Jingxiang (taken from Architectural Journal's website: http://www.aj.org.cn, 2016).

4.2. FINANCIAL BYPASS AND CHINESE "MASTER BUILDER"

Comparing to SHoP's merging of financial criteria with design intent, ambitious Chinese architects have emerged to challenge the inflexible DBB mode by proposing an Architect-led design to build (ALDB) - a "turn-key" workflow (Jiang 2005). This holistic strategy emphasises architect's control over processes and requires direct collaboration with manufacturers, contractors, and shipping companies. To bypass potential barriers, practitioners have ventured into rural areas in China where modern construction techniques became inconvenient. Professor Zhu Jingxiang and his team from The Chinese University of Hong Kong (CUHK) have for example been endorsing a digital IPD mode supported by customising ARCHICAD

software. In the "Playroom" case (figure 5, right), the financial argument considered minimising cost while maximising spatial experience. The team engaged a wood factory for prefabricating building components which guaranteed a "direct fabrication" workflow integrity and achieved an equilibrium in architectural performance. Cutting-edge digital technologies have been introduced to China by digital "home-grown" architects as well. Professor Yuan Feng from Tongji University spearheads the first generation of enthusiasts in robotic tectonics.

5. Conclusion

The barriers that prohibit modern Chinese architecture from revolutionary change in the digital era can be summarised as 1) the inadequate authority architects have in the project organisation, and 2) the dispersive project delivery integrity in comparison with manufacture industries. The world is witnessing a universalization of computation in architecture. The adoption of this trend both ideologically and materially in China has become their manifesto of the 21st-century modernization. Meanwhile, the inertia of China's booming urbanisation ensures one of the largest building markets until 2030. Investments in the disciplinary innovation of architecture appear necessary. SHoP's strategies amplify an architect as director, engineer, and manager - a digital master builder. Not only does the firm thus manage to convey explorative design languages, they guarantee increasing profit as well. Yet, a fundamental difference from the Chinese context lies in the liability differentiation. In China, new architect returnees have emerged to test the applicability of innovative strategies. Many have successfully bypassed an arguably immature construction system and achieved novel outcomes with regional practices.

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PREDICTIVE URBAN ANALYTICS

Exploring Choice Modelling and Revealed Preferences for Urban Design

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Abstract. Since the rise of generative design, a morphogenetic process of designing has emerged where algorithms are used to explore potential permutations of a solution to find the best design option. Yet, on a subjective level, identifying what option is considered best has often proven to be difficult. Hence, the paper discusses a foundation research to investigate prototypically subjective judgments concern matters of value and preference defined by end users in generative modelled urban design outcome. To do so the paper will introduce and outline research findings in the field of Micro-Economics, in particular its subcategories 'Choice Modelling' as a method and 'Revealed Preferences' as a methodology to assess whether user preferences can be identified and engaged as 'preferred' design options. In the paper the research will outline in greater depth the theories behind Choice Modelling and Revealed Preferences, a field that studies the behaviour of individuals, and its relevance for urban design, in particular Computational Urbanism. The paper discusses how Choice Modelling can analyse design outcomes and conclude and speculate about its use in an applied context.

Keywords. Generative design; Aesthetic judgment; Choice modelling; revealed preference; design evaluation.

1. Introduction

Since the rise of generative design, a morphogenetic process of designing has emerged where algorithms are used to explore potential permutations of a solution to find the best design option. As a result, designers have access to a tool that permits them to generate several potential design outcomes (Martin 2010). The designer is given the task of assessing and identifying which outcome out of the

generated options is superior to the rest. One can observe that this potentially can result in an open-ended process and hence one can ask how evaluation criterion can be established to narrow down and limit an open-ended design process? An open-ended process approach in design and the designer's relationship to the generative process has been a long-standing topic of Greg Lynn's 'in-folding' approach since the 1990s (Massumi 2000) but often in practice the open-ended design process must be terminated using either subjective or objective criterion.

1.1. COMPUTATIONAL URBANISM / PARAMETRIC URBANISM

Modern urban design is venturing towards that of parametric design where designers input various performance criteria and the building form is to be generated as a direct result of the inputs. Architecture and design is developing a data-driven design process where designing is no longer focused on the subjective decisions of the designer but rather the behavioural mannerisms of society and the surrounding context of the built form. As a result, urban planning and the creation of urban form is being developed according to "population thinking as opposed to typological thinking" (Verebes 2014) with the result being site specific, customised designs that are a direct reaction to the dynamic attributes of the urban context. Therefore, with the use of computational and parametric urbanism, it is now possible to contemplate the architectural shift from designing with aesthetic judgements to that of data-driven designing founded on objectivity and urban data. Observing that objective judgements can be addressed through computational and parametric urbanism one can asks where this leaves a subjective judgement of generated outcomes?

1.2. AESTHETIC JUDGEMENT

For the scope of this paper, a general description offers that objective judgements concern matters of empirical and mathematical fact whereas subjective decisions typically involve methods of value and preference (Mandik 2000). Objectivity can be weaved into the design process through parameters such as materials, sustainability, structure, manufacturing methods or cost constraints. Parameters discussed above that are subject to research are Grasshopper Plugins such as Ladybug / Honeybee and Karamba. Subjectivity, on the other hand, is more difficult to quantify as the values and preferences of the designer are intrinsically linked to their cultural, religious, social, and economic positions to name a few. With this in mind, design decisions are often made using subjective qualities. This paper questions how subjective design decisions could be understood and potentially generated computationally with computational and parametric urbanism.

In addition, this research also queries as to whether there currently exists a method (tool) and methodology (justification for using the tool) that bases the design decision process on user values and preferences.

1.3. RECOMBINANT GROWTH

In their 2016 book 'The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies' Erik Brynjolfsson and Andrew McAfee explain

the "Recombinant Growth" model developed by the economist Martin Weizman (1998) which, in short, is a mathematical model of a new growth theory that is not dissimilar to generative design. The theory offers an "innovation-as-building-block view, where both the knowledge pieces and the seed ideas can be combined and recombined over time." (Brynjolfsson & McAfee 2016) The authors argued that Weizman's "first generating new ideas, then filtering them" concept has now been widely applied by web-based start-ups due to readily available and affordable masses of data, vast computer power and the "more eyeballs" principles where the more participants looking at the same data, the more combinations can be discovered.

Weizman's theory is relevant for this research as it provides the initiative background of the paper. After outlining Weizman's theory, Brynjolfsson and McAfee describe a case study where the concept of "first generate new ideas, then filtering them" has been applied on evaluating a design. In the case study, Carlsberg breweries attempted to update the bottle and label for Belgium's Grimbergen beer, the world's oldest continually produced abby beer. Carlsberg sought to update the brand but had concerns about damaging its reputation with a design change. His solution was to develop a method to better understand what the existing target market thought about the varying design options and which option was preferred. This case study founded on observation of user behaviour is directly linked to the level of research required for this project as users are able to choose their preferred design option out of numerous generated designs based on their subjective standpoint.

1.4. CHOICE MODELLING

Carlsberg, according to Brynjolfsson & McAfee (2016), employed 'Affinnova', a company "supporting recombinant innovation [who] helps its customers with the second of Weizman's two phases: sorting through the possible combinations of [innovation-as] building blocks to find the most valuable ones." Affinnova made use of the mathematics of Choice Modelling in order to sort through the design options. The Authors explain that:

"Choice modelling quickly identifies people's preferences - do they prefer a brown embossed bottle with a small label, or a green non-embossed one with a large label? - be repeatedly presenting them with a small set of options and asking them to select which they like best. Affinnova presents these options online via the Web and can pinpoint mathematically, the optimal set of options (or at least come close to it) after involving only a few hundred people in the evaluation process. For Grimbergen [Affinnova's client] (2013), the design that resulted from this explicitly recombinant process had an approval rating 3.5 times greater than that of the previous bottle." (Brynjolfsson & McAfee 2016)

Based on the Carlsberg case study, one could conclude and propose the following research investigation to develop a subjective evaluation model for generative design, stating that:

If Choice Modelling can identify on a subjective level which, out of multiple design options, is the most approved beer bottle design, then one could potentially

adopt this method to identify on a subjective level, the 'best', or most 'fit' option of multiple generated design outcomes.

Thus, the paper discusses a foundation research to propose the generative modelling of urban design founded on subjective judgement, in particular, the values and preferences of the designer. The research will use 'Choice Modelling' as a method and 'Revealed Preferences' as a methodology to assess whether user preferences can be identified and engaged as 'preferred' design options. Both Choice Modelling and Revealed Preferences are subcategories of the field of Micro-Economics; a field that studies the behaviour of individuals (Bade & Parkin 2001) and are introduced and outlined in the following paragraphs.

2. Choice Modelling

Choice Modelling, as outlined by econometrician Daniel McFadden (2000) in his Nobel Prize lecture in Economic Science, is the "micro-econometric analysis of choice behaviour of consumers who face discrete economic alternatives". It uses either 'stated preference' or 'revealed preference' techniques that are used to estimate non-market environmental costs and benefits (Bennett 2005).

2.1. STATED PREFERENCE

A 'stated preference' involves questioning a group of people regarding their preference for varying resource management strategies. Each question asked is termed a 'choice set' (Bennett 2005) and is only one outcome chosen out of generally three or four alternate strategies. Each choice set is grouped by a common set of attributes. Each alternative has one constant that is included in all choice sets, and the remaining attributes are altered to provide variety to the question being asked. Respondents are provided with two alternatives, with their choice of preferred alternative demonstrating their willingness to choose one attribute over another. For example, in the case of a cost-benefit analyses, if one alternative is monetary, it is possible to estimate the respondent's willingness to include non-market environmental benefits described by the other attributes suggested (Bennett 2005).

2.2. REVEALED PREFERENCE

Revealed preference on the other hand, is a method of analysing choices made by individuals through their purchasing and consuming behaviour (Samuelson 1938). Where Stated Preference are mostly individual interviews based on a selected preference, i.e. asking the interviewee to view one or two images and asking them which of the two they prefer, Revealed Preference techniques attempt to understand consumer behaviour and the existing and past constrains on the individual such as their budget or particular interests such as visits to a certain webpage.

2.3. DISTINCTION BETWEEN BOTH AND MOTIVATION TO CHOOSE REVEALED PREFERENCES

Choice Modelling adopts both revealed and stated preferences. One can differentiate best by stating that revealed preferences are already made by the individual in the past (thus revealing what they have chosen prior) and stated preferences

documents choices made under experimental conditions (thus stating what preference exists at present). Given the increased ability to digitalise data and big data (Brynolfsson & McAfee 2016) and the research's interest in computing and automating processes, the following research will focus on *revealed* preferences as these are potentially already in existence and can be accessed through governmental or economical survey platforms, i.e. bureau of statistics in various countries.

Regardless, both sets of preferences are highly dependent on understanding human choice behaviour.

2.4. UNDERSTANDING HUMAN CHOICE BEHAVIOUR

A fundamental aspect of economics is understanding human choice behaviour (McFadden 1973). This task proves to be difficult as each act being observed is under the influence of external factors that cannot be controlled. The solution, as developed by Daniel McFadden, is to "make statistical inferences on a model of individual choice behaviour from data obtained by sampling from a population of individuals (or sampling from a population of experience levels) for a single individual" (McFadden 1973, pp 105).

The selection criteria for Choice Modelling consists of the objects of choice and sets of alternatives available to decision-makers, the observed attributes of decision-makers, and the model of individual choice and behaviour and distribution of behaviour patterns in the population. (McFadden 1973, pp 106)

The process of designing and implementing a Choice Modelling experiment is outlined by Bennett as follows:

1. Define the issue - interaction with bio-physical scientists
2. Define the attributes - including via focus groups with respondents
3. Define the levels
4. Select an experimental design
5. Design the questionnaire
6. Implement the survey
7. Data analysis
8. Report compilation (Bennet 2005)

2.5. CONCLUSION CHOICE MODELLING

Based on the Choice Modelling introduction above, the paper argues that there is great potential to combine the ability to document subjective opinions using Choice Modelling with the analysis and digital generation of urban form. This paper outlines our interest in designing and implementing Choice Modelling questionnaires to the public realm to define which urban design aspects are favourable over others, whether it be the building form itself, aspects of street frontage, varying facades and so on. Choice Modelling techniques permit the potential to combine the subjectivity of personal opinion with the objectivity of mathematics and parametric design to generate an infinite amount of urban designs founded on the likes of the public.

3. Implementing Choice Modelling

Global marketing research and analytical consulting firm Decision Analyst have implemented the Choice Modelling technique as well as a large range of modelling and simulation projects across a variety of industries including retail, restaurant, automotive, high-tech, and health. They employ an array of measurements and experiments in a ”cause and effect” style of working to find the ”underlying truth” (Decision Analyst 2016) and the ”real reasons for consumers’ buying decisions” (Decision Analyst 2016). They conduct experiments that contain a predetermined set of realistic conditions such as asking the consumer which brand they would buy of the same product. These brands are presented visually and in the appropriate context of advertising, pricing, packaging, features, promotion, and other variables (Decision Analyst 2016) and often help in the optimisation of product designs, price sensitivity, brand strategy and more.

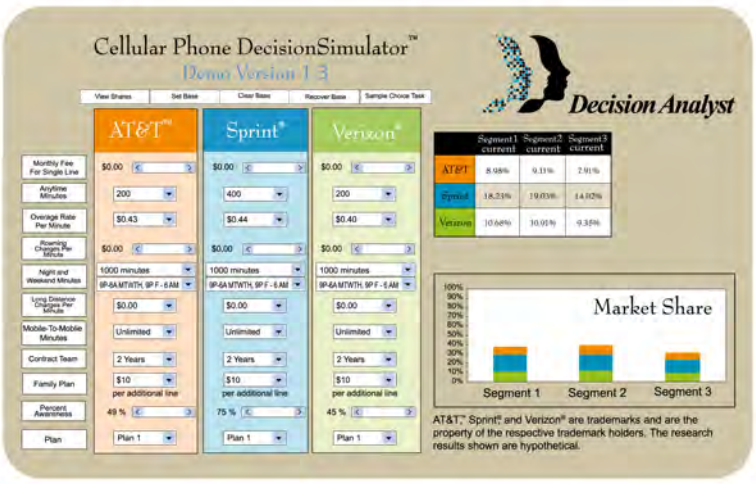


Figure 1. Example of the DecisionSimulator system interface (Decision Analyst 2016).

This method of analysis is effective as it is “tailored to the specific objectives and constraints of each brand” (Decision Analyst 2016) and can be utilised to explore a variety of marketing scenarios (figure 1). Their findings are placed into a programmed Simulator that the company has developed that permits ‘what-if’ style scenarios to be explored through the simple entering and configuring of inputs. The benefit of this Choice Modelling technique is that consumers are able to provide information deeper than the simple ‘what they will buy and what they will not buy’. Choice Modelling permits the gathering of information of the roles of price, brand image, brand name, media advertising and an unlimited range of attributes that have a role in the decision making of the consumer. With this information, it is possible to explore new product designs, marketing strategies and an adjusted method of attack.

4. Issues Associated with Choice Modelling

In creating these Choice Model designs however, there is the issue of determining the number of alternative choice profiles to be offered in each choice set (figure 2) (Bennett 2008). Choice Models have the capacity to offer multiple alternatives within a single choice set, therefore the selection of a particular set of options is critical and is to be selected according to the desired outcome of the study. The number of choices offered to the respondent is purposely limited in a means to avoid burdening the respondent with complex choices (Bennett 2008). This often ensues in the minimisation of the description of choice profiles to only a limited number of attributes (figure 3). The negative impact of this may include reducing a complex cognitive task into something simpler that may not be as effective in representing the task. In the case where there are many attributes and levels involved, there is an inclination to reduce the number of profiles offered for selection in the choice model in a means to limit the cognitive task (Bennett 2008). The importance of this is evident in the decision-making process of the respondent as tasks too complex to consider may result in the deferring or avoiding of choices.

Table 3 – Variables used as regressors in CM models

Variables	Description
Cost	Amount that households would pay in extra rates (or rent) each year to fund improvements
Vegetation	% of healthy vegetation remaining in floodplains
Waterways	Kilometers of waterways in catchment remaining in good health
People leaving	Number of people leaving country areas each year
Reserve	% of water resources in catchment not committed to the environment or allocated to industry/urban/ irrigation uses
Age	Age of respondent (in years)
Member	Dummy coded (1 if member of organization associated with environmental conservation)
Education	Dummy coded (1 if respondent has post-secondary qualification)
Income	Income of respondent
Gender	Dummy coded (1 if respondent was male)
Farming	Dummy coded (1 if respondent or family member associated with farming)

Figure 2. Example of variables used as regressors in CM models (Rolfe & Bennett 2008).

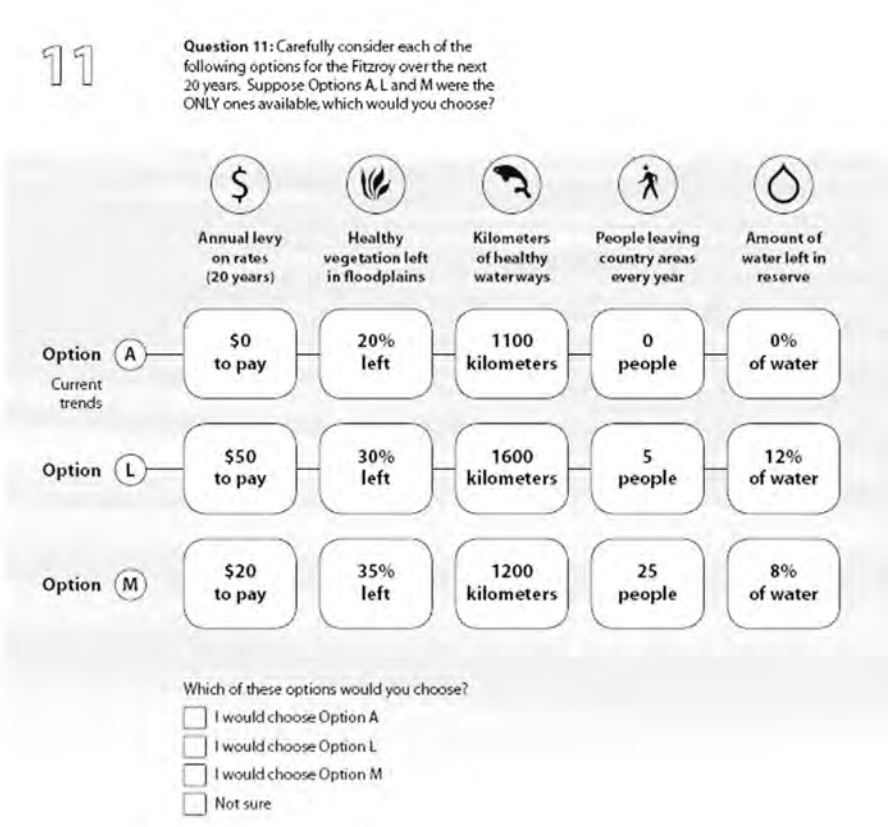


Figure 3. Example of a choice set in the three-alternative version (Rolfe & Bennett 2008).

5. Next Steps: Linking Choice Modelling to Generating Urban Design Outcomes

This paper is the beginning of an extensive study into the combining of Urban Design with Computational Urbanism through the methods of Choice Modelling and revealed preferences. In the case of this proposed research, we are proposing the use of the econometric methods of analysis of user behaviour to urban design where the consumers are developers who aim to identify which design, out of the generated proposed urban design options, possesses the most promising economic alternative (preferred by public).

Combining Choice Modelling with the generation of urban design outcomes has enormous potential in the development and proposal of design solutions where it provides an option to tailor designs to the demands of the public. The analysis of public requirements and desires in relation to urban design is possible through Choice Modelling, as demonstrated through this paper and in particular in the Carlsberg Case study. Whilst the case studies mentioned above are predominantly

related to brand and product marketing, this paper aims to extend the same principles used to the urban design field.

Choice Modelling can be implemented into the early stages of design development by providing end users with variations of generated designs, placed in a real-world situation. This could be presented through the lens of a Virtual Reality headset or perhaps a photoshopped image. The next step would then be to ask them to choose which design option is preferred according to their subjective opinion and documenting the findings. Extensive case studies of this would then be documented into a data pool and used as a base set of data for a machine learning algorithm where the subjective decisions of the end-user could be analysed, learned, and eventually repeated without the need for human interaction for future urban designs.

The resulting analysis can be implemented into early stages of design development and can act as a tool to reduce planning delays associated with developments and design proposals. Consumer-retaliation and feedback is often provided at a stage that is post concept-design. Any changes required to be made due to public feedback are often provided after the document set of drawings is produced and presented, making it a time-consuming process to change any aspect of the design post-production. Using Choice Modelling to provide community feedback at an early design stage is therefore crucial in reducing any negative feedback that occurs after a development proposal is lodged. The earlier that consumer feedback can be incorporated into the design, the smoother the transition the project is submitted through the development approval process and hence the shorter the planning delay.

The combining of Choice Modelling with urban design would in our understanding involve the following process:

- Defining of an area to research (suburb or urban space)
- Finding the target market and outlining what data best describes the preference of a homebuyer looking to purchase in the specified area hence using already revealed preferences.
- Define and compare the desired urban design attributes to be analysed
- Develop an experimental Choice Model based on the chosen Revealed Preference values.
- Generate urban design outcomes using the outcome of the Choice Model analysis.
- Implement existing data (GIS / e-planning) as well as revealed preferences / choices already-made by individuals (statistics and house preference data) into the above model to further the accuracy of the design outcomes. This would be achieved via a software program that can access the webpage and its relevant data.
- Create an extensive data depository of e-planning, statistical and spatial data that is accessible online via a webpage.
- Develop and generate a set of designs based of this new data utilising VR and image processing as a method to display designs
- Test out each set of designs using Choice Modelling methods and document the resulting data.

- Apply this data into a Machine Learning algorithm to analyse, learn and repeat the subjective design decisions made by the end-user

It becomes evident that there is great potential to combine the subjective values of human design decisions into the automated process of digital design generation using Parametric controls. The urban design and development process is able to be streamlined with the incorporation of community involvement at early design stages using Choice Modelling analysis techniques. The benefit of this process is enormous as not only does it shorten planning delays, but urban designs are more readily and easily integrated with the desires of society. This generation process provides a gateway to combine the requirements of the community to the world of design and architecture with the ability to use real live data to influence and drive design decisions.

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Parametric and Generative Design

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TOWARD TEMPORAL AND PUNCTUAL URBAN REDEVELOPMENT IN DYNAMIC, INFORMAL CONTEXTS

An Adaptive Masterplan Driven by Architectural Interventions Using Multiagent Modeling

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Abstract. This paper presents design research speculating on new planning approaches for informal urban sites that enables coordinated planning to operate within the realm of spontaneous, bottom-up redevelopment. In opposition to the /tabula rasa/ Modernist development, this project reacts to the dynamic metabolism of the village and engages with the rapid turnover of the built environment of the village as a mechanism through which to implement incremental redevelopment. A radical reorientation of the object of masterplanning, this replaces the singular image or document as the guiding authority with a collection of opportunistic adaptations, temporal sequences, and localized procedures. Enabling this approach is a computational approach that analyzes the morphology of the public space network to identify opportunities to address issues in the composition of the village. A multiagent system driven by weighted random walks through the circulation network conducts local analyses of the urban fabric while changes are made and proposes potential modifications to discrete areas. The model simulates the potential for such a planning tool to be used over a long time span and updated with empirically gathered data, having the benefit of flexibility and resilience in the face of the changing and unregulated conditions in the context of informal urbanism.

Keywords. Generative design; responsive masterplanning; informal urbanism; network analysis; agent-based modeling.

1. Introduction

The village-in-the-city (城中村 : `chengzhongcun,' also sometimes called `urban village.') phenomenon in Chinese cities-the result of rigid restrictions on migrant mobility and lack of effective urban planning restrictions in what are technically considered as rural lands-has been well documented (Chung 2015; Mullan et al. 2011; Wang et al. 2009). However the majority of research focuses on those villages-in-the-city that are most embedded in the urban fabric (Zacharias et al. 2013). The villages of Haizhu island in Guangzhou are unique in that they are still surrounded by the remnants of agricultural land, the Wanmu Orchard and Yingzhou Ecological Park, despite occupying a geographically central position within Guangzhou. This fact sets them apart somewhat from the pressures of the megalopolis and renders them more autonomous and self-contained units, which makes them well suited for limited studies like this one.

The test case is sited in Xiahzhoucun, one of the larger villages in Haizhu. Typical of many villages-in-the-city, there is a high degree of unregulated construction (and reconstruction following demolition) throughout the village to replace decaying structures or to increase housing capacity. This fact makes the strategy of punctual interventions appealing in contrast to a comprehensive masterplan (Kerez 2016). These construction processes are the sociomaterial interactions at the heart of the urban metabolism and influenced the decision to work with an insistently dynamic, process-based approach in the project.

Unlike many villages-in-the-city, the population growth of Xiaozhoucun is not dominantly driven by migrant workers, but by students who attend the nearby University Town and artists associated with the Guangzhou Academy of Fine Arts drawn to the quietness and tranquility of the village (Qian et al. 2013; Andersson 2012; Qian et al. 2012). Much of the attractive urban quality of Xiaozhoucun derives from the experience of walking through the warren-like alleys of the village and the small pockets of open space, especially along the river. Thus, the project focuses on the network of public space as the village's characteristic feature and primary object and agent of change.

1.1. URBAN NETWORK MORPHOLOGY

Historically, the dominant practices of urban morphology have been concerned with defining morphological regions through identification of historical forms of development (that is, with similar relationships between of ground plan, built fabric, and land use) and identification of typological processes (Sima & Zhang 2009; Whitehand 2001; Oliveira et al. 2015). A trend toward more procedural definitions is apparent in recent methods that merge the analytical power of computational processing with the precision of GIS software (Jiang 2000). This project builds on work in Urban Network Analysis, that represents urban morphology as a network of intersection nodes connected by links that correspond to street sections, a method sometimes referred to as the primal graph (Sevtsuk & Mekonnen 2012; Porta 2006).

One criticism of primal graphs is that a single section of the street may actually have many different qualities, resulting in an analysis with a lower resolution

and one that varies unevenly depending on the network morphology. Sevtsuk and Mekonnen address this concern by including building entrances into the network as additional branches from the street segments, enabling the use of floor height, use, or occupant load to add weighted values to the urban analysis. This works quite well in contexts with a high proportion of standalone buildings, however in Xiaozhoucun the built environment is a near-continuous fabric of buildings. In this project we address the concern by subdividing network segments at locations where the street width changes significantly and by adding additional segments at the location of party walls that separate adjoining buildings. This gives a much finer resolution to the network and renders the building volumes a more integral part of the network itself.

1.2. MULTIAGENT SWARMS

In order to address the informal context of the village without imposing a deterministic plan, the project uses a swarm of agents to conduct localized, rather than total, actions. These agents both read the urban network morphology analytically and encapsulate behaviors for exploration and redevelopment that capture the intelligence of the village metabolism (Leach 2009). Swarm intelligence is often seen as a useful way to replicate or work within informal urban settlements because it reproduces an environment where behavior logics engage and adapt to one another in the absence of a central control or guiding masterplan (PanahiKazemi & Rossi 2013). Furthermore, an agent-based system is well-suited to dynamic modeling and the responsiveness it requires (Kuo & Zusinger 2010). Within network analysis, multiagent systems have also been shown to be effective tools for identifying network features such as clustering patterns (Harel & Koren 2001; Alamgir & von Luxburg 2010).

2. Methods

2.1. NETWORK DEFINITION

Within the model, the existing village was redrawn as a network from a standard cadastral plan. This network is formatted as a customized half-edge mesh such that mesh edges represent segments of circulatory space or party walls between adjacent buildings. Unlike many urban network analyses, the model also engages with the mesh faces, which represent individual parcels (built or open), such that the half-edge datastructure is not merely a technical expediency, but a direct analogue of the representational schema. Mesh faces and edges are defined as object classes with a number of properties for metadata such as built height or clear width. Even the relatively compact village of Xiaozhoucun is composed of over 850 parcels and 3800 edge segments, so the model also includes methods for automatically importing and assigning the metadata values from a standard figure-ground image file making initial conditions easy to update. Figure 1 shows this base image file and the resultant mesh rendered with either edges or faces visualized.



Figure 1. Left: Figure–ground map of the site from cadastral plan (including building heights: taller buildings have darker hues); Center: Edge representation within simulation model; Right: Face representation within simulation model (including building heights: open parcels are shaded black).

2.2. AGENT DEFINITION

Preliminary analysis indicated that the village's circulation network, though extensive, was characterized by discontinuities and long, dead-end alleyways. The agent walks have two purposes: the first is to stochastically record bottlenecks and clusters in the circulation network by recording the aggregate traffic volume over time (these values are stored as properties of the mesh edge class). The second is to conduct comparative analyses of the urban network localized at the agent's position to indicate potential for minor changes that would open up significant new connections.

The half-edge mesh provides the ground for the agent swarm. Agents occupy nodes and are able to move along any incident half-edge with a non-zero width. The direction of travel is selected randomly from a list of the available directions and can be weighted according to the path widths (direct backtracking is precluded except in the case of a dead-end). The random walks were tested with three parameters for direction selection (figure 2, columns): an unweighted list in which each possible direction was counted once; a linear weighting in which possible directions were counted according to their width in meters, wider paths thus having a greater chance of being selected; and an exponential weighting in which possible directions were counted according to one half of the square of their widths, wider paths having a much greater chance of being selected. The exponential weighting resulted in many sections of the network being ignored while the unweighted option had the most even coverage. Ultimately it was decided that the bias toward larger thoroughfares resulting from a linear weighting was the best option for the model because these paths were also high traffic areas in the real world and because it would lessen the impact on the urban character created by the narrow alleyways.

Another parameter that was introduced was to give the agents a lifespan, after a certain number of steps, the agent would be removed from the simulation and a new agent spawned at a randomly selected public space. This was done to prevent agents from becoming stuck permanently in a loop or dead-end and unbalancing the results. Testing with different age parameters (figure 2, rows) showed that a high threshold of 90 steps did not do much to combat the problem of repetitive movements, while a low threshold of 10 steps often prevented the random walks from spreading far enough from their initial locations. A threshold of 50 steps was chosen for use in the model.

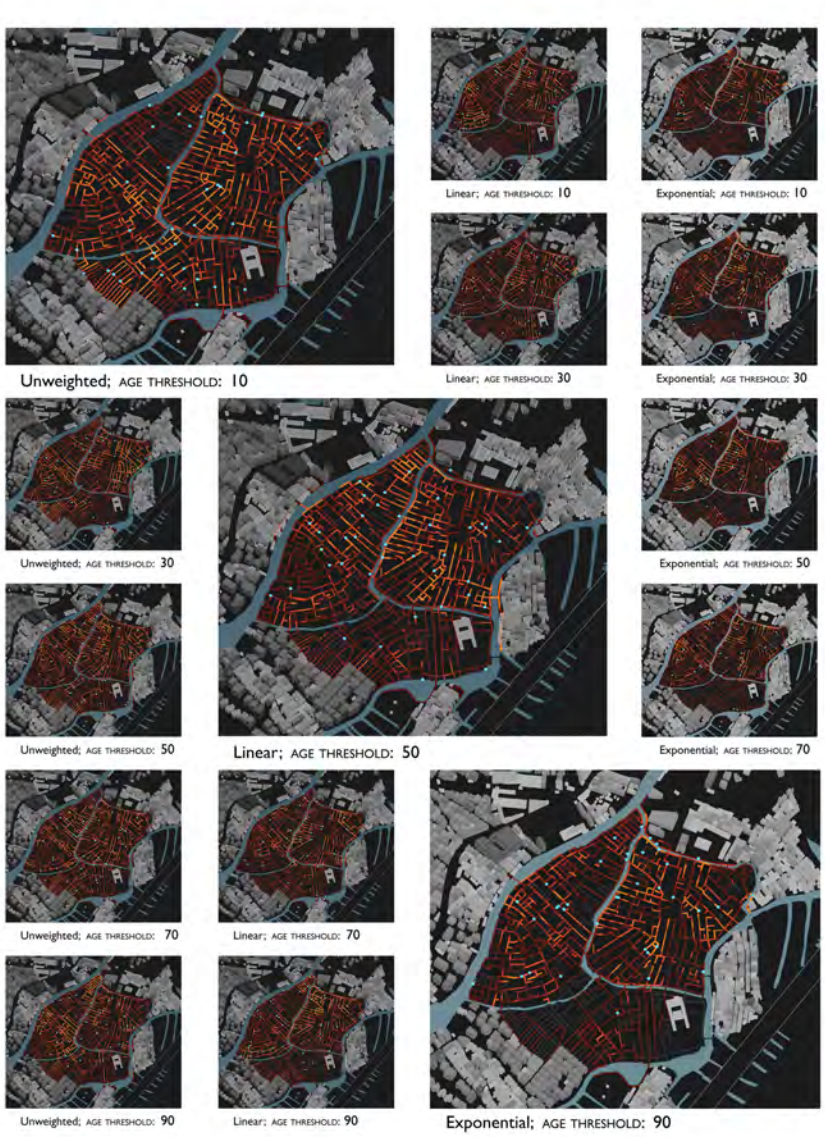


Figure 2. Accumulated traffic patterns of multi agent random walks after 500 frames with different parameter sets. The selected option is in the center.

2.3. LOCAL NETWORK ANALYSIS

In order to assess the potential of a location for alteration, each agent is programmed to calculate the local graph of all navigable edges that could be reached from its current location within a limiting depth, in this case 75m (this limit value was selected after early tests indicated that the selected edge always fell within this

range). The travel distances required are compared to the distances for the same points that would be possible if all edges of the mesh were used, including those that are currently not traversable. The point from the first graph that had the greatest reduction of distance is selected and the shortest path to it highlighted. Any segments along that path that are not traversable are identified as potential shortcuts and an aggregate value counting the number of times an edge is designated as a potential shortcut is saved as a property of that edge (figure 3).



Figure 3. Left: A depth map from an agent location over the circulation network, localized to 75m; Right: the same depth map including also non-traversable edges as potential connections with the most impactful shortcut highlighted in blue.

2.4. TEMPORAL REDEVELOPMENT

As the simulation runs, the mesh faces periodically assess the total traffic and shortcut values over all their perimeter edges. If the sum exceeds their own persistence value (a value assigned at the beginning of the model that declines as the building ages) they are considered for replacement. At most, one face per interval is selected, if that face has an existing building on it, it is demolished and rebuilt at a higher density. The reconstruction is defined on the model of the village's existing pattern of building (new construction is typically concrete frame with brick infill) and of recycling material from adjacent demolition (pending more in depth site surveying, we assume that existing structures are masonry cavity wall construction typical of older, low-rise building in the village). The material available defines the maximum height of the new construction in the model. The primary feature of the proposed new construction is the definition of open pathways at any edges that had accumulated high shortcut values as well as greater setbacks on any edges that had recorded excessive traffic volumes compared to their previous width. After a parcel is selected for reconstruction the agent swarm and edge values reset and new agents are spawned from various public spaces in the village. Subsequently all agent walks and analyses use the new width values in their operation. Figures 4 and 5 show screenshots of the model in operation.

3. Results

After running the simulation for 5000 cycles, the model had widened or opened 653 edges and reconfigured 379 parcels (32.3% by count or 29.5% by area)-62 of them as new open plazas (figure 6). From the built floor area, 70,000m2 of the original 190,000m2 were replaced and extended with the result of nearly doubling the FAR from 1.27 to 2.48, reaching a total built area of 370,000 m2. Interestingly, the sites of redevelopment are distributed widely across the site as truly punctual interventions and not primarily within common zones. Interventions increased in frequency as the simulation progressed due to the advanced aging of the original building stock.

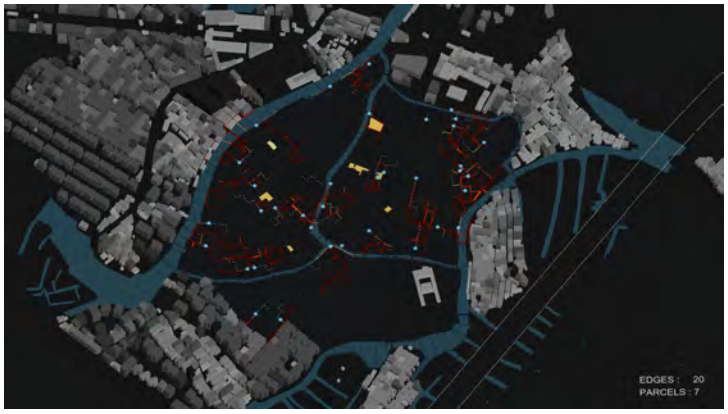


Figure 4. The path of the agents random walk is recorded as a traffic value by the edges. Currently calculated shortcuts are shown by the dashed line. The combination of these values is visualized as the color of the edges.

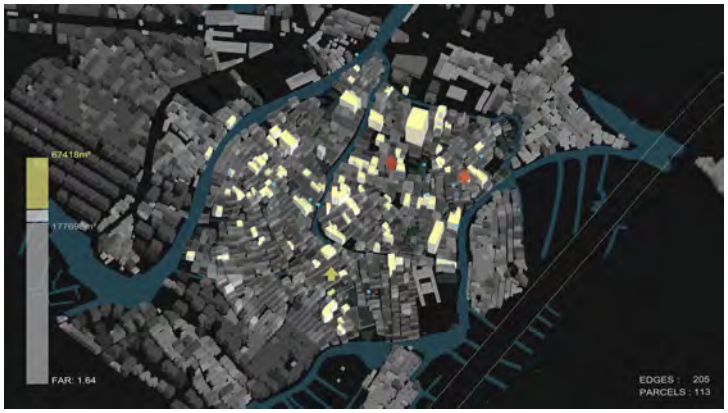


Figure 5. A volumetric visualization of the simulation with a live tally of total built floor area. Yellow volumes are new constructions. In-process demolition (red arrows) and reconstruction (yellow arrow) can be seen in this frame.



Figure 6. The edges and faces modified after the simulation has run for 5000 frames.

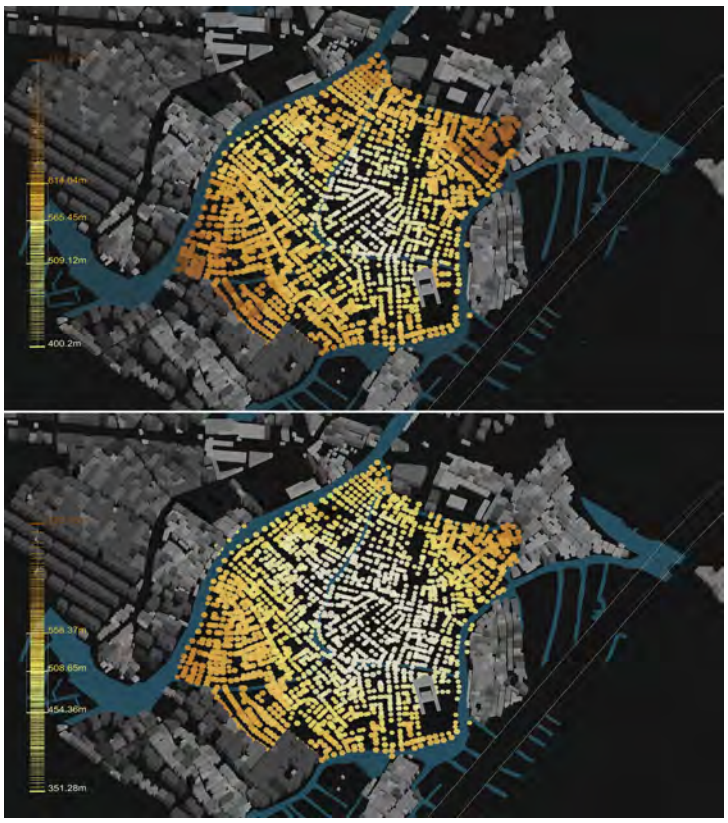


Figure 7. Comparison of eccentricity values before and after the simulation has run.

With regard to the original goal of addressing inefficiencies in the circulation network, the eccentricity of the network was calculated before and after the simulation was run: from each node in the half-edge mesh the geodesic distance to every edge was calculated and the highest value stored. The median eccentricity of the initial circulation network was 565.45m and the diameter (the single longest

direct distance between two points) of the network was 775.73m. These values decreased to 508.65m and 702.13m, respectively (figure 7). This change was effected by opening up around 4.14km of new alleyways, a sizable number in comparison to the pre-existing network length of 16.7km, but quite small when one realizes the average addition was only 6.93m. An additional 417m of pathways were widened slightly by 1 meter increments.

4. Conclusions and Further Work

The model developed here demonstrates the capacity to guide development in an informal context without resorting to a totalizing plan-even with only a few simple parameters. Despite the lack of centralized coordination, the selection of parcels is consistent and overall urban composition remains coherent and functioning throughout. The decrease in the median eccentricity and diameter values shows how strategically positioned modifications can offset relinquishing control of the end result. While it might be possible to optimize the impact of interventions by working back through the alterations and removing redundant changes, we feel that would go against the primary goal of a planning tool that is meant to be reactive and resilient to external changes. A few concerns about the model behaviors include the homogeneity of the potential network-new alleys and new bridges are treated the same, though a bridge would be significantly more expensive-and whether the acceleration of intervention frequency, though reflective of real obsolescence concerns, allows the analyses to sufficiently inform the selection process.

As a design tool, there are a few drawbacks. Creating the initial network may be a negligible step in well-documented areas (the same format is used by *openstreetmap.org*), but in informal contexts, this information is less likely to exist. Tracing the urban network is time consuming and prone to introducing errors. The method used for data input from image files was, however, quite successful in reducing the time needed to populate the model with fuller data. Better methods for controlling the flow of time in the model, especially starting and stopping the simulation, would improve the performance and memory loads as well as allow adjustments to changing onsite conditions.

The simulation would benefit greatly from increased empirical data regarding the existing building stock, especially the building construction techniques, age, and extent conditions. Currently, the values used for these are too homogeneous to indicate how the model would perform in actual use. Similarly, more data about the social and programmatic use of space would be useful to compare against the projected changes and to fine tune the agent behaviors.

Within the computational model there are two aspects that warrant further work. The first is to address the static, discrete nature of the mesh faces. Given the small size of the average parcel, increases in overall density will face a limit based on the necessary vertical circulation. A natural solution would be to allow adjacent, small parcels to share a staircase or elevator core, enabling taller constructions to also be considered. This would would require more communication between a mesh face and its neighboring faces, but once implemented could be used for a number of purposes, such as air rights negotiation and privacy from vis-à-vis relationships.

The second focus is to study more closely how the multiagent random walks compare to other methods for defining clustering, such as spectral graph analysis, and to develop a more standardized set of metrics to compare agents with different parameters so that they can be benchmarked against these static methods.

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AUTOMATIC 3D MODELING OF KOREAN TRADITIONAL ARCHITECTURE

Applying Parametric Design

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Abstract. Korean traditional structure is constructed as prefabrication jointed in largely characterized by its unique components under the specific rules of assembly and proportion. This point is a double-edges sword. Because, while various shapes and sizes of components based upon an objected-oriented form appear the potential possibility of producing changeable prototypes to build up, these various characters of components and several jointed methods has made difficulties to handle. Accordingly, an automatic 3D modeling algorithm is focused on the methodology of changeable prototypes of Korean Traditional architecture keeping traditional jointed methods with setting various characters of components

Keywords. Korean traditional structure; Parametric design; Generative three dimensional modeling; Hanok.

1. Introduction

The traditional architecture of Korea is a building made by connecting components and components. Because of this characteristic, the connection method between the various components plays a very important role. However, it is difficult to easily describe how to connect its components. In addition, to make understanding of architecture easy, it should be made into three-dimensional drawing, not two-dimensional drawing. Through these works, we will be able to facilitate modernization of the traditional architecture and reinterprete traditional architecture. It also needs to simplify the way of connecting architectural elements with architectural elements in terms of modernization and explores various forms derived from traditional architecture to give insight to architects. From this point of view, this study shows how three - dimensional models can be automatically generated and how traditional architecture can be transformed from a modern point of view. In this case study, this paper deals with the Daengung-jeon of Sudeoksa Temple

is jointed with various components. This complicated structural performance has been only taken to few craftsmen with 2D drawing. Accordingly, it has led a typical formation and performed time-consuming process from unmanageable diversity of components' types and relationship. However, in the context of the digital era, parametric design provides a new approach to architectural methodology of Korean traditional architecture. For this approach, a sample of Daengung-jeon of Sudeoksa Temple which is an oldest wooden building in Korea is utilized. The whole scale of Daengung-jeon of Sudeoksa Temple (19,152mm x 13,195mm) is set as a maximum size, and the distance and angle between component and component are constrained. In the process of the study, two methods are proposed. First is a bottom-up method assembling from the smallest component composed of the building. And second, a top-down method is used for reconfiguring from a form to component (Park 2011). In this paper, Grasshopper is applied for functional relation between components by automatically calculated process. In this study, a correlation between components applying structure function relationship is essential (Kwon 2014). It also leads on an automatic formation of Korean traditional architecture keeping relationship between components as well as makes time efficiency on the process (Stavric 2011) The objective of study is to establish parameter networks involving the correlation between components and develops a parametric algorithm for the automatice generation of 3D model of the Korean traditional architecture based on parameter networks.

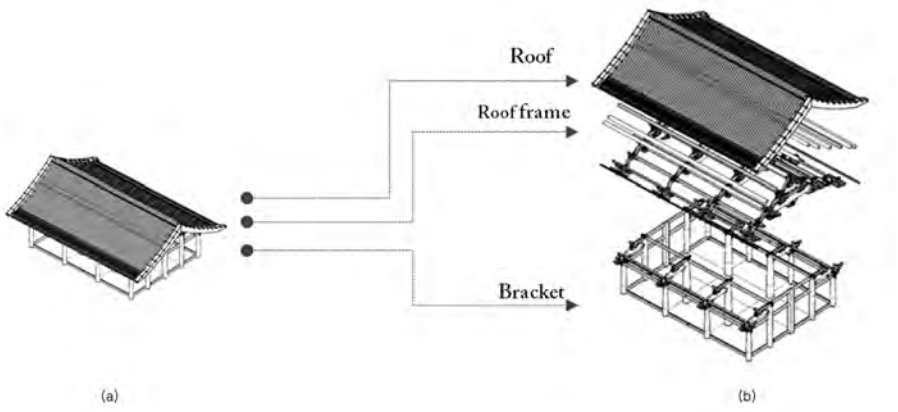


Figure 1. (a) Daengung-jeon of Sudeoksa Temple. (b) The detail drawing of Daengung-jeon of Sudeoksa.

2. Literature Review

Korean Traditional structure is constructed as a free-form building jointed in largely characterized by its unique components under the specific rules of assembly and proportion (Ahn 2011). Thus, the geometric dimensions of a wooden component as well as the proportional relations between the components of a part assembly can be parameterized (figure 2).

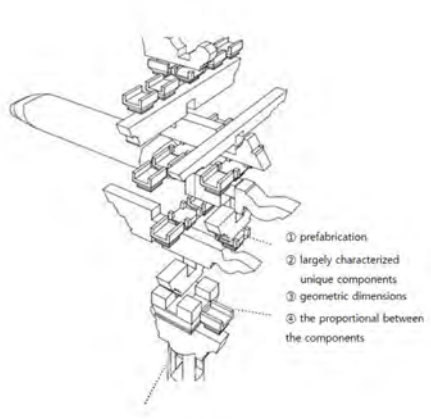


Figure 2. Details of the joint structure between components.

2.1. VARIOUS CHARACTERS OF COMPONENTS

While various shapes and sizes of components based upon an objected-oriented form appear the potential possibility of producing changeable prototype to build up, these various characters of components and several jointed methods have made difficulties to handle.

2.2. BUILD ONLY FEW CRAFTSMEN'S INSIGHT

In addition, the wide characters of components have been dealt by only few craftsmen's insight with 2D drawing. A natural interaction is characteristic of this tool which can be considered by hand work. This condition has supported more difficulties to make the system for generalization (Kim 2010).

2.3. 2D DRAWING

As follows, the drawing is not a smart medium, but rather, a code based on standards and conventions. This 2D drawing has two limits. First, the act of drawing differs from cognitive mechanisms underlying the creative process. It is just like recording. Second, the drawing process excludes physically relevant aspects that in the real world drive the generation of forms (Tedeschi 2012).

3. Research Method

Simulation research is applied as a research method. It is useful both developing and testing theory, and simulation occurs when a replication of a real-world contains within it dynamic interactions that are the result of manipulated factors. Based on simulation research, the flow diagram shown in figure 3 was conducted.

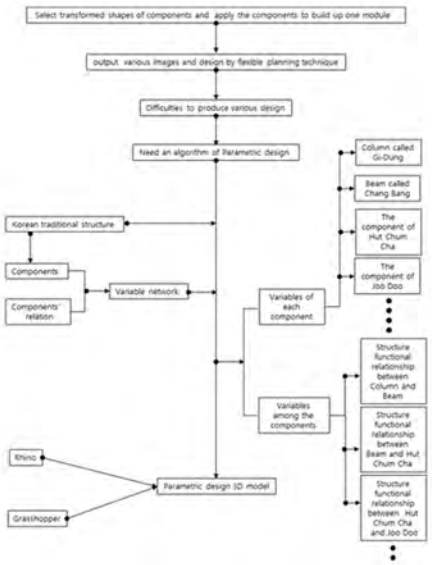


Figure 3. Flow diagram of aumomatic 3D modeling of korean traditional architecture.

4. Hierarchical Relations of Components in Bracket Unit

In the figure 4, the number of components is classified into the layer with its name because one of key features of Korean traditional structure is that the architecture builds on bottom-up system. At Level 1, a column as a vertical component is set. In addition, at Level 2, a beam as a horizontal component is jointed. From Level 3 to Level 6, the "Bracketing Unit" part is formed in total balance by crossing the horizontal components and the vertical components in figure 4. Figure 5 illustrates the characteristic of components, and how the different shapes of components assemble each other following the rule of Korean traditional structure .

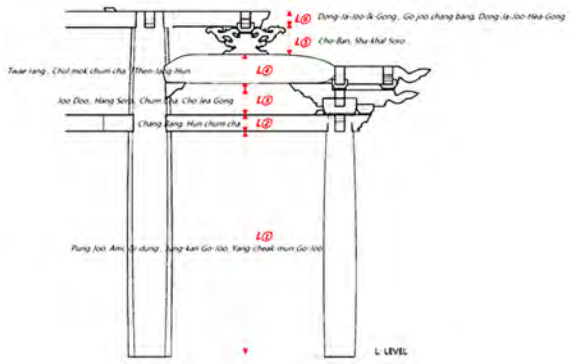


Figure 4. Hierarchical Classification of components based on the level .

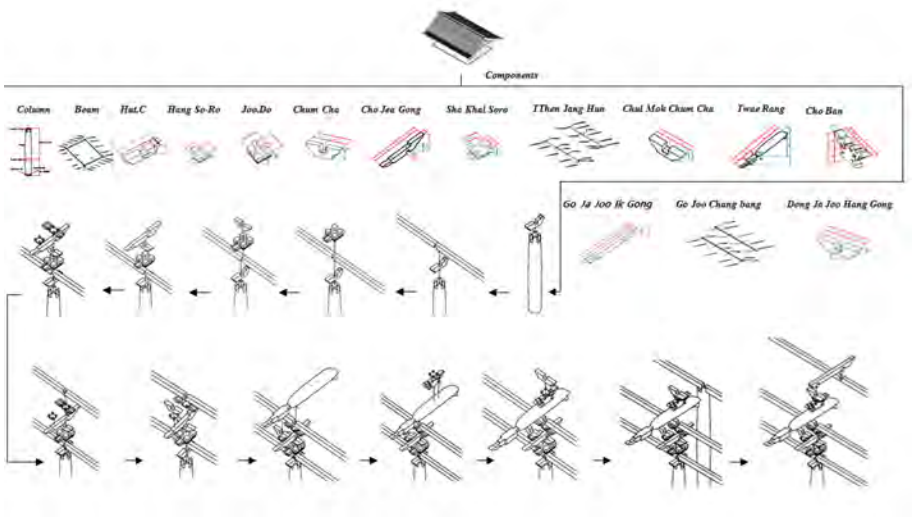


Figure 5. Assembled differently components based on rules of Korean structure.

5. Variations of Spatial Configuration Using Parameter Relationships Between Components.

Figure 6 shows the network among elements of each component in Korean traditional architecture. The depth and width of the whole scale and the height of the column are set as independent variables. In addition, all remaining components are set as dependent variables; the height of the lowest column has a function relationship with the height of others. In addition, the depth and width of the whole scale has a correlation with the depth and width of all the components. On the other hand, specific components having the shape of a cube and a cylinder have the same value of depth and width. (Kim 2010)Therefore, the specific components of depth and width have parameter relationship with depth and width of the whole scale at the same time. In brief, depending on the component's shape and position, the number of variables is different and parametric relationship between components is definded.

5.1. AUTOMATIC 3D MODELLING BASED ON PARAMER NETWORK

The parameter relationship network (figure 6) is a foundation to set up the algorithm to creat automatic 3D model system. Figure 7 shows the algorithm to produce a 3D model automatically using the relationship between components of "Bracketing Unit part". When the numerical value of one variable is raised, the numerical values of remaining variables are autimatically raised according to parametric relationship. In other words, when one component's dimension extends, the dimension of all remaining components are automatically extended. As mentioned earlier, the problem of modernizing Korean architecture is how to handle with many components efficiently keeping the joint system. Accordingly, the algorithm suggests automatic modeling methodology by parameter relationship between components.

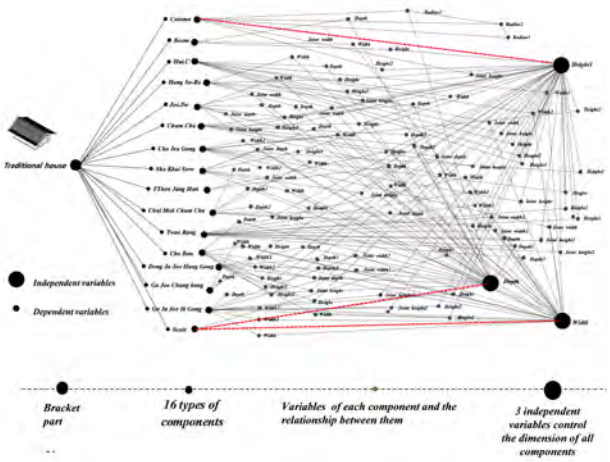


Figure 6. Parameter relationship network.

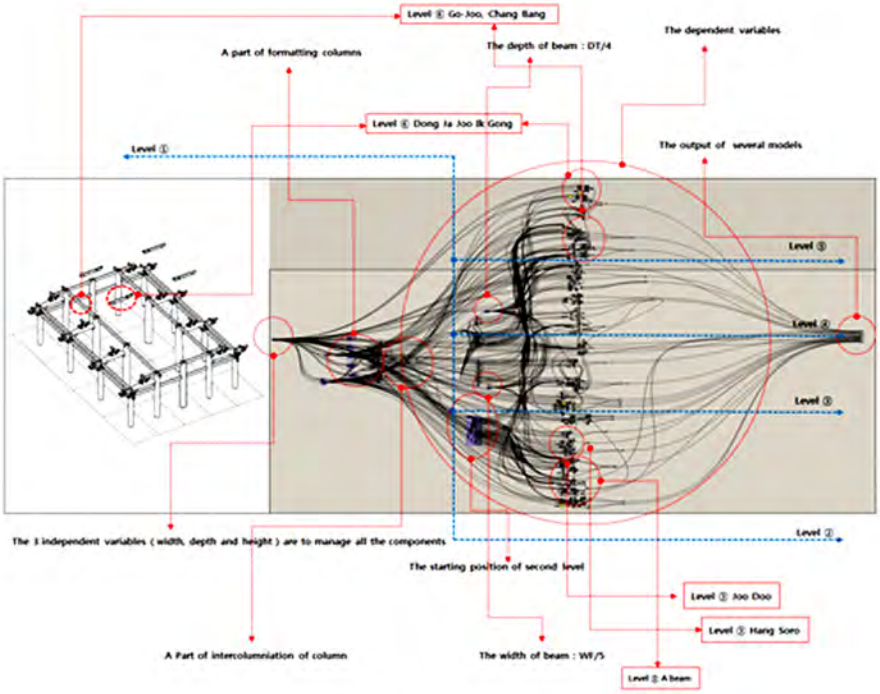


Figure 7. The algorithm according to the functional relationship between components.

Based on the algorithm, figure 8 indicates the parametric relationship between components. All columns' 3R are followed by the value of a width or the depth of whole size. In addition, the height 1 of a column called Pung-Joo has parameter relationship with others' height. Figure 9 shows parameter relationships between a column and a beam.

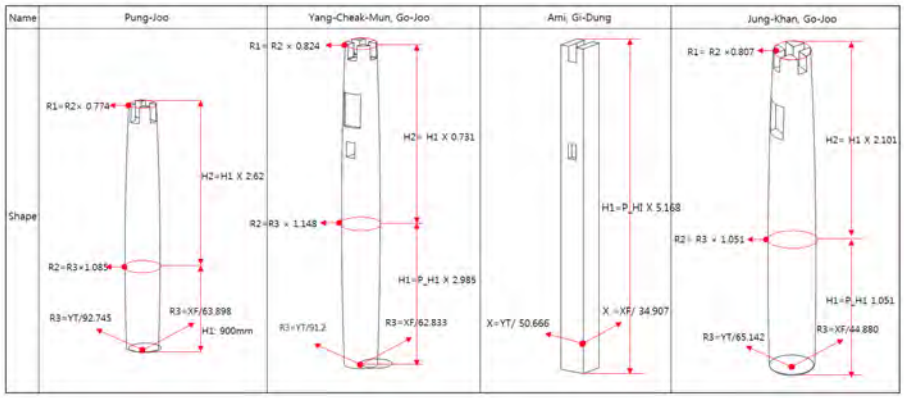


Figure 8. Structure function relationship between columns.

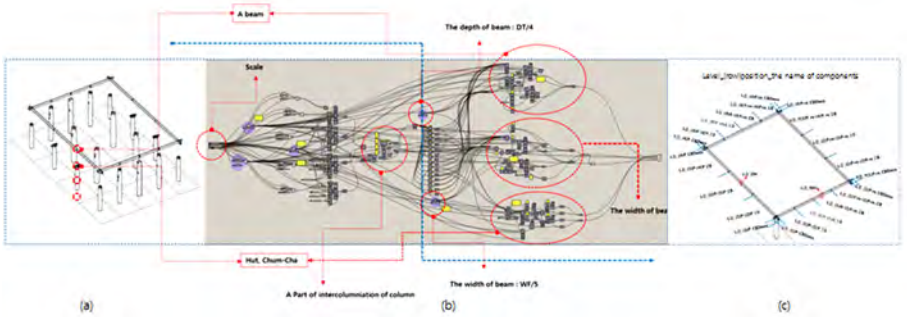


Figure 9. (a) The position of 3 elements. (b) The algorithm of 3 elements. (c) Each code-name of pieces in a beam.

Since Korean traditional architecture is constructed by joints of members and members, it is very important how to connect the members. In order to show an example of joint method between components and components, the method selected in this paper is a method of connecting columns and beams. Chang Bang, a kind of beam, is a horizontal component that connects a column to a column at the top of a column. Figure 9 shows how the columns are arranged and connected to the Chang Bang. The width and depth of Chang Bang is inter-related to width and depth of all upper components. Figure 9 shows the results depending on the applying the functional relationship between components or not. Figure 9 (a) shows unmatched connection between components with no functional relationship

and figure 10(b) figures out the connection applying the functional relationship between components. In this way, to create a natural joint between the component and the component, a function that reflects the relationship between the parameters needs to be used.

In the similar way of modeling a column and a beam, we can prooduce various structures obtained applying different parametric value of components using the parameter relationship network (figure 11).

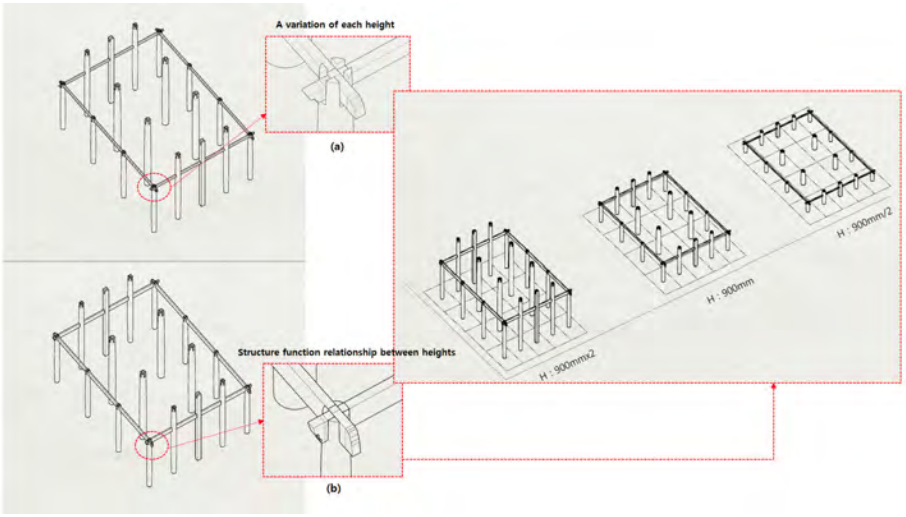


Figure 10. Comparing joint part. (a) non parametric relationship (b) parametric relationship among components .

6. Conclusion

The paper suggests an automatic 3D modeling methodology for the process of Korean traditional architecture. In order for traditional wooden architecture to make harmony with the environment and culture of modern society, the process to build up Korean traditional architecture has to be flexible and efficient (Park 2009). This study has attempted to deal with the difficulties of 3D modelling of the traditional architecture and demonstrated how to apply algorithmic parametric design to produce automatically 3D models. This algorithm for an automatic 3D modeling that combine digital technology with traditional building system can conduct the potential possibility of traditional architecture that was previously impossible to realize because of technical shortage in the past. In addition, for modern people living in a different environment and society from a past, the methodology with algorithm of a study shows some suggestions of exploratory space derived from formal changes of traditional wooden architecture. Therefore, this an automatic 3D modeling method provides a starting point for the evolution of the process for modernization of Korean traditional architecture.

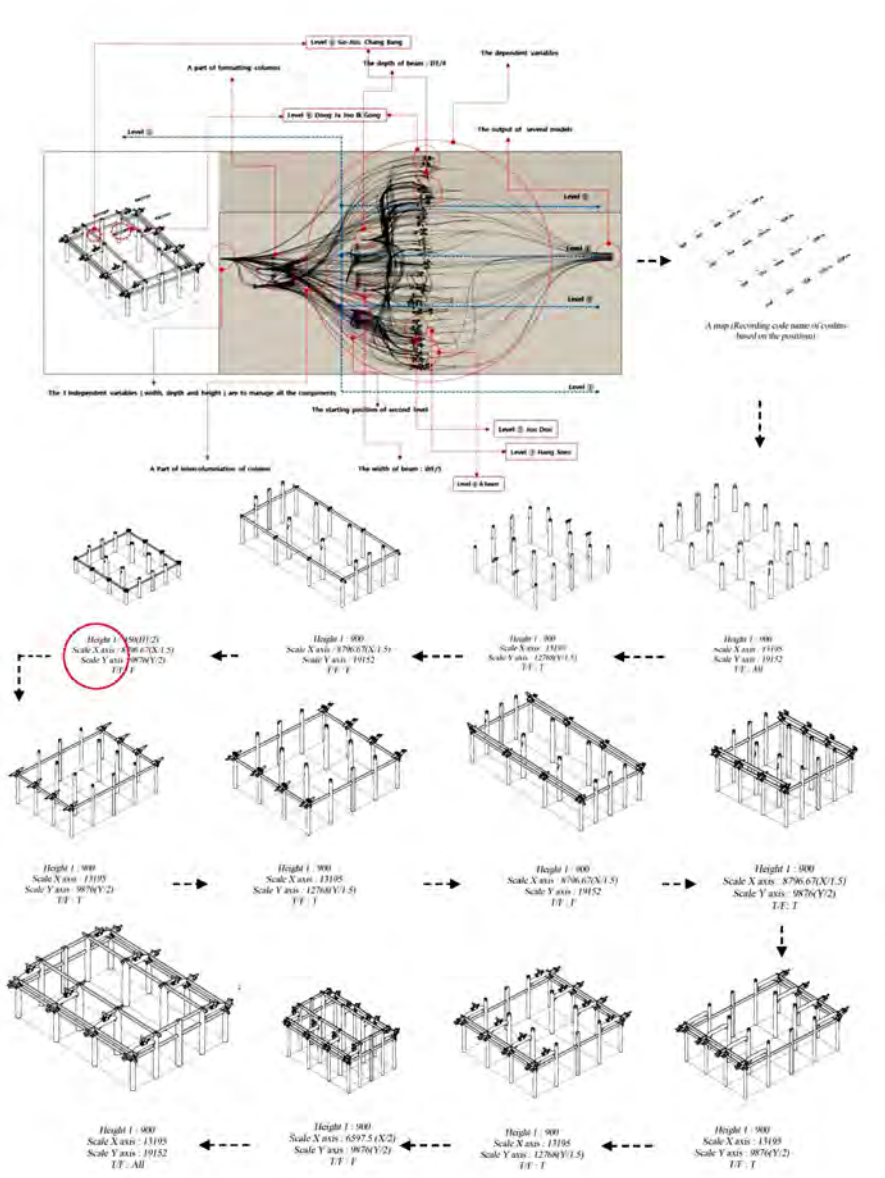


Figure 11. Various forms explored applying different parametric value of components .

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THE MATHEMATICAL LOGIC BEHIND LAI THAI

A Geometric and Parametric Analysis of the Traditional Thai Pattern, Kanok Sam Tua

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Abstract. This paper investigates Lai Thai, a traditional Thai pattern whose grid structure and frame pattern have been clearly defined, in textbooks, as being created by freehand drawing. There are similarities between Lai Thai and patterns that are referred to as Look Thai. In this paper, one reference that Thai artisans follow: the "Kanok Sam Tua" pattern is analysed. Geometric analysis for the external frame and parametric analysis for the interior frame were used to unveil the underlying mathematical logic of the traditional Thai pattern Kanok Sam Tua, which is created from two triangles, and a circle. The results show that the exterior frame of the pattern follows three main rules related to (1) Proportion, (2) Point, and (3) Direction. This research also demonstrates that Lai Thai can be investigated using geometric and parametric analysis. In addition, it reveals that there is stochastic mathematical logic hidden behind the metaphorical Thai lotus bud design.

Keywords. Thai pattern; Mathematical logic; Visual algorithm; Generative art and architecture.

1. Introduction to Lai Thai and Hypothesis

"Lai Thai" or traditional Thai patterns are a part of Thailand's national art heritage. Royalty, Buddhist clergy, noblemen, and those who are at the upper levels of the social hierarchy have exclusively used them for generations. Knowledge of Lai Thai has been limited to Royal artisans, monks, and artisans, who have been trained over a long period to draw by hand. For generations, master artisans have passed down the skill set required to produce these patterns. Phrathewaphinimmit was the first to document this in 1943 (Tiamsilchai 1987). He indicated that Lai Thai was at

risk of disappearing because the design of traditional Thai patterns was dependent upon the drawing skills and creativity of artisans. However, there are underlying similarities in aesthetics that indicate the patterns are Thai, even though the hand drawn patterns are subject to artistic interpretation. Therefore, one reference that all Thai artisans use, the Kanok Sam Tua pattern is considered for investigation in this research. Principles based on mathematical logic are applied to identify similarities and differences that take into consideration the artisan's subjectivity and aesthetic preferences. The purpose of this research is to find the mathematical logic hidden behind the design of traditional Thai patterns. It is hoped, through the principles of generative grammar, and shape grammar, this may lead to understanding the impact Kanok Sam Tua has had on other Lai Thai patterns. A similar analysis has already been attempted on other patterns, such as Islamic (Alani & Barrios 2015), Chinese (Stiny 1977), Korean (Lee et al. 2010), and African (Gokmen 2012). However, this is the first time it has been applied to a traditional Thai pattern.

Traditional Thai patterns are known to have evolved from observations of elements in nature such as trees, leaves, flowers as well as animals, and in biology, it has been stated that natural systems like trees and leaves can be investigated further using the L-system (Lindenmayer 1968).



Figure 1. Left - Kanok Sam Tua (Kanok pattern with three bodies), which takes root from the lotus bud. Right – An example of using Kanok as a decorative pattern in Thai architecture (Ayutthaya).

According to Thai artisans, the Kanok Sam Tua pattern is used as a reference for all of their artwork. In textbooks on Lai Thai, authors, such as Chay Tiamsilchai (1987), have described the "Kanok" pattern using curves and triangles, explaining that it was derived from the shape of the lotus, a flower representing purity in Buddhism. However, it has not been claimed that Lai Thai, or any other form of traditional Thai art can purely be derived from geometry, let alone a computational method. In the early 2000s, Pichet Klunchun, a contemporary Thai dancer and choreographer, stated that all the structures used in the Thai performing arts were lines derived from two geometric forms: curves and triangles (Klunchun 2016). Klunchun observed that in traditional Thai dance, curves representing cir-

cular and curving movements collected energy then brought it back to the center of the body, in accordance with Buddhist cosmology. Triangles are found in basic classical Thai dance movement, and on the tympanum of traditional Thai architecture they reference the sitting position of the Lord Buddha. These shapes not only influence visual art forms created by performing artists, they inspire the artistic thinking of the nation. Thus, it could be hypothesised that because the Kanok Sam Tua pattern is quite structured, its creation process could be explained through mathematical logic.



Figure 2. Curves and triangles in Thai classical dance (courtesy of Mr. Pichet Klunchun).

2. Method of Analysis and Scope of the Research

The aim of this research is to uncover the mathematical logic behind the Kanok Sam Tua pattern.

Initially, the formation of the Lai-Thai pattern was observed using the inverse problem method. This method takes a comprehensive view of the overall pattern to run a systematic geometrical analysis with the aim of understanding, through mathematical logic, the causal factors that influence the construction of a pattern. Therefore, the observations are divided into two types: historical and mathematical, using a Thai pattern described in the book Jitdrathanee (Chinchusak 2012), as a reference. Asymmetrical and symmetrical Lai Thai patterns were observed and categorized according to their symmetrical characteristics. This paper focuses on a particular Kanok pattern called "Kanok Sam Tua", which translated means "Kanok pattern with three bodies". Considered as "Mae Lai" or a master template for its generative variation, Kanok Sam Tua has been identified as an asymmetrical pattern, which is complicated due to the directional interconnecting forms within the pattern itself. A scanned sample of the pattern, which was handwritten, and hand drawn in 1943 from blueprints created by Master Phrathewaphinimmit, is shown in figure 1 - left (Tiamsilchai 1987). This pattern has a framing triangle, framing curves, and a rectangular grid, which make it suitable to serve as a guideline for this study. Two types of structure were observed, the exterior structure (grid structure, and pattern frame) and the interior structure (Garb Lai, Kanok body 1, Kanok body 2, Kanok body 3).

Secondly, when the Kanok Sam Tua patterns were analysed geometrically it was revealed that the external frame of the "Kanok" was derived from the shape of two triangles and a circle, which were proportionally framed by a rectangle. Consequently, rules that dictate the creation of these shapes were formulated using a set of proportional points and direction. These rules illustrate the underlying

principles, which artisans have been following for centuries.

Thirdly, the interior frame followed the same rules; however, these curves were created by joining points set by an external frame. Therefore, they followed the direction rules; however, the magnitude of the curvature would be subject to the artisan's preferences. These curves were further analysed using the Rhino-Grasshopper platform because parametric functions enabled the simulation of all the possible curves that could be formed. The parametric features were programmed on numerical sliders, which allowed the curve's precision to be adjusted to represent the artisan's version of the pattern.

3. Analysis of Exterior Pattern Frame: Investigation using Mathematical Logic

On the surface, it could be questioned why lotus buds, in particular, were selected to determine the outline of the pattern. This may be because, in nature, lotus buds differ based on species, and according to time taken to grow. The exterior pattern frame was investigated using stochastic geometrical analysis to discover where mathematical logic ends and individual artistry begins.

The grid systems were accurately traced to investigate the logic behind the formation of the external frame's pattern. An assumption was made that the external frames were set before the interior part was detailed. The Kanok Sam Tua image has always been created using a two-dimensional scale; therefore, it was possible to raster the image onto the Autocad 2D platform. Following the Kanok Sam Tua image, the units were keyed into Autocad as 5, and the image scales were matched accordingly. Based on the image, there were 2 grid system intervals, (1) 5 unit intervals or module A and (2) 7.2 unit intervals or module B, as shown in figure 5.1a. Module A running on Grid X was repeated three times (x1, x2 and x3) and repeated four times on Grid Y (y-x1, y-x2, y-x3, and y-x4), as shown in figure 3(1) below.

Module B ran mainly on Grid Y and was repeated four times (y1, y2, y3 and y4). The origin of module B was further investigated to find out how the artisans had attained the magic number of 7.2 units. After a few attempts, it was discovered that to attain 7.2 units for module B, artisans would first need to set a centre point or Point A at (x3, y-x2), and then draw a perfect circle with a diameter of two modules, as shown in figure 3(2). From there, the starting point at (0, 0) or Point B could be linked to the highest point of the circle at (x3, y-x4) or Point C. The diagonal line that intersects with the circle at Point Y is 7.2 units from the base of grid X, as shown in figure 3(3).

Similar principles to attain the units for module B were applied, the highest point in parallel with the centre point is at (x3, y4) or Point D. The next diagonal line is joined from Point B to Point D, which is the main diagonal line for the Kanok pattern. The diagonal grid line is 62 degrees from Point B to D, as shown in figure 3(4). Following the same principle that was used to attain units for module B, the intersection point between the main diagonal line and circle were identified, and named as Point F, as shown in figure 3(5). A point underneath Point A, or Point G, was evident in the Kanok pattern and it was discovered that when a new horizontal

grid was set from point F, it intersected at a particular point of the vertical grid x3. The new horizontal grid is referred to as grid y1a, as shown in figure 3(6). These grid lines helped to determine the proportion of the shapes that emerged from the mathematical diagrams. This is discussed further in part 6.

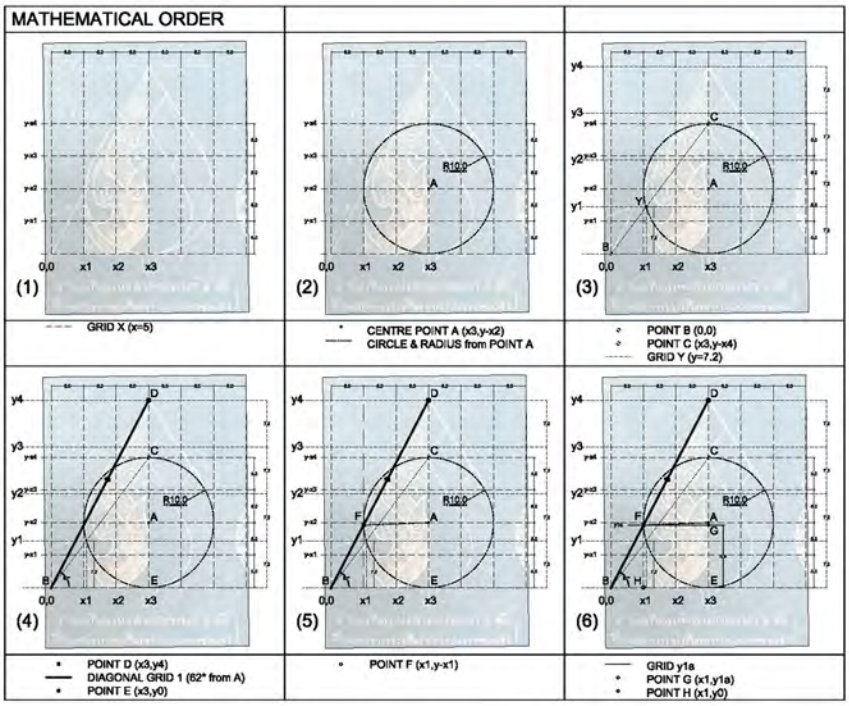


Figure 3. Mathematical order of the Kanok Sam Tua pattern.

4. Parametric Analysis of the Interior Pattern: Initial Rules Investigated and Discovered

Following the investigation of the external frame, a similar method was attempted with the interior frame. The points of intersection between the curves could be identified; however, the curvatures were difficult to mimic as they were drawn freehand on the image. According to the textbook, these curvatures were based upon the individual artisan's interpretation. Setting the points to guide the curves was not mentioned in the text. To achieve this, it was realised that software, which could simulate the possibilities of different curves was required. As the curves form a repetitive sequence, an investigation was attempted using shape grammar software. Unfortunately, currently available grammar software suites: Shaper 2d V3.1 and Interpreter (Li 2005) do not allow for the construction of curves. Therefore, Rhinoceros with the Grasshopper plug-in was chosen as software to investigate the curves in more detail.

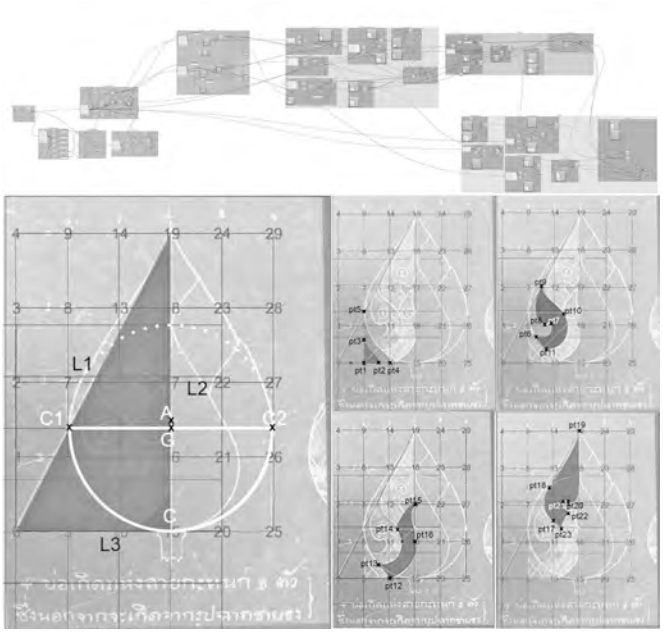


Figure 4. Parametric analysis of the interior structure using Rhino-Grasshopper software. .



Figure 5. An MD slider on Grasshopper adjusted for different degrees of curvature using a Bézier span.

First, by following the rules above, the mathematical instructions for the exterior structure were keyed in, for the points and curves, as shown in figure 4. Then, a visual algorithm was developed to create a script for the Kanok Sam Tua pattern. The algorithm revealed the semantic relationship between the external geometry and the internal curves, which could indicate where the Euclidean transformation would occur. From this investigation, 23 points (pt1, pt2, ...pt23) and 20 curves were defined for the Kanok Sam Tua pattern. From initial observations, some points were known to be on the Grid, and some had to be calculated. Grasshopper sliders helped to place points accurately on the original drawing. After that, the degree of curvature was calculated using a numerical slider for the catenary, and an MD slider for the Bezier (cf. figure 5). It was discovered that the artisans had some degree of freedom to create the interior frame, even if the external geometrical frame defined it.

Example of initial rules: Overall rules

Rule no.1: According to the mathematical order discovered, a grid structure composing of x=1.44y is placed, where Grid x repeats 5 times, and Grid y repeats 4 times. There are 29 points listed on the grid system (P1, P2, P3, ...P29). Rule no.2: The Kanok Sam Tua pattern is framed by a triangular outline composed of 3 lines, L1 (P0->P19), L2 (P15->P19), and L3 (P0->P15). A curve C comprising of a horizontal line joining C1 and C2, where G is the mid-point between them, also shapes it. Rule no.3: When a full circle is plugged into curve C, the circle's center A is identified. Rule no.4: The Kanok Sam Tua pattern (K3) is composed of the following sub-shapes: S0 (Garb Lai), S1 (Kanok body 1), S2 (Kanok body 2), and S3 (Kanok body 3). Rule no.5: The Garb Lai (S0) starts on the bottom left at one third of the way along the triangular outline of the pattern. Rule no.6: Kanok body 1 (S1) and body 2 (S1) sit on the Garb Lai (S0). Rule no.7: Kanok body 3 (S3) sits on Kanok body 1 (S1) and Kanok body 2 (S2).

5. Investigation Outcomes and Discussions

The exterior structure and the interior structure of the Kanok Sam Tua pattern are investigated and discussed.

5.1. EXTERIOR STRUCTURE

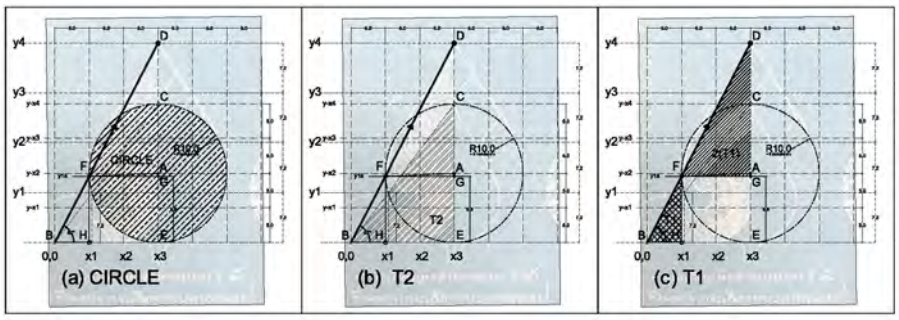


Figure 6. (a) Circle (b) Supporting T2, (c) Main Triangle T1.

From the grid outline of the image traced in Figure 3(6), two triangles and a circle were identified, as shown in figure 6. The discovery sequence for these shapes: the circle on figure 6(a) was found before T2, as shown in figure 6(b), and then the main triangle T1, as shown in figure 6(c). The circle was also used to set T2, and afterwards T1. The central circle is the reference point, which the Kanok pattern is based on. The main triangle T1 forms the overall shape defined from Point B to D following the gridline x3 down to Point E. At the same time, it was found that this triangle was proportionally the same as the smaller triangle, formed from Points B to F and H. It can be assumed that the other smaller triangle formed from Point B to F and H was the basic T1, while the other triangles were scaled up from these proportions. These triangles were extrapolated for further examination, as shown in figure 7 below.

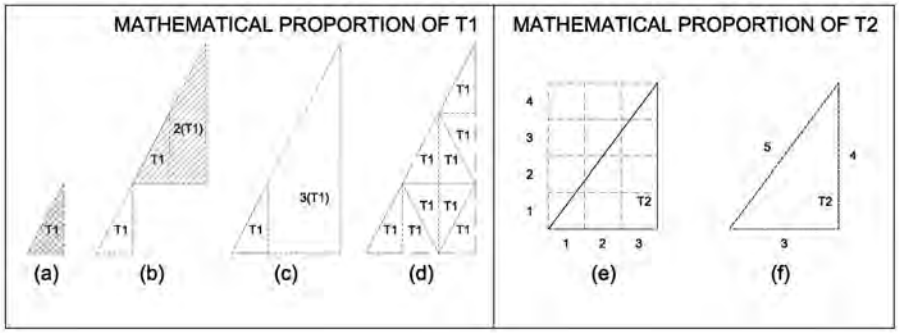


Figure 7. Left - Mathematical proportion of T1. Right - Mathematical proportion of T2.

After a thorough examination, it was found that T1, as shown in figure 7(a), was the smallest triangle. Moreover, the main shape had been scaled up by a factor of two, as shown in figure 7(b), and by a factor of three, as shown in figure 7(c). It would not have been possible to create T1 proportionally without the division at Point H and the grid y1a. Therefore, it could be assumed that this proportionality would have been calculated, and then drawn by the artisan using the grid division method learned through trial and error. This relationship between proportion and points has allowed artisans to reproduce the Kanok Sam Tua pattern with precision. Further investigation of the work methods used by the artisans would be useful to develop more understanding of the rules involved.

T2 is the supporting triangle that sets the second grid system of module B, which is 7.2 units. Without module B, T1 could not have been formulated. The underlying principle used to create T2, was found to follow the same principle that is used by the Pythagorean Theorem, which has a fundamental relationship to other Euclidean geometries (Pythagorean Theorem 2016). Figure 7(f) clearly illustrates that the T2 principle is similar to the 'Pythagorean equation', a2 + b2 = c2.

This discovery triggered more questions: How did the Thai artisans learn about proportion and ratio? Did Indians, Chinese, or others who had discovered the theorem independently influence their understanding of mathematics? Did they learn the art of mathematics as part of a long apprenticeship? These unanswered questions are beyond the scope of this research; however, they could be used as a basis for future research.

Apart from that, the direction, proportion, and points were consistently charted from left to right; however, working alternately between the top and bottom was also permitted. The direction is considered as positive (+ve), which was evident from the external frame's interior curves. Furthermore, the symmetrical effect was created by mirroring from the left to the right. In summary, it was discovered that the Kanok external frame pattern followed three main rules related to (1) Proportion (2) Points, and (3) Direction.

The influence of the Kanok Sam Tua pattern on Royal Thai Architecture was investigated further by studying two examples: (1) the Royal funeral pyre for the late King Bhumibol Adulyadej, designed by the Fine Arts Department, as shown in figure 8(a), and (2) A traditional nobleman's house, as shown in figure 8(b) below.

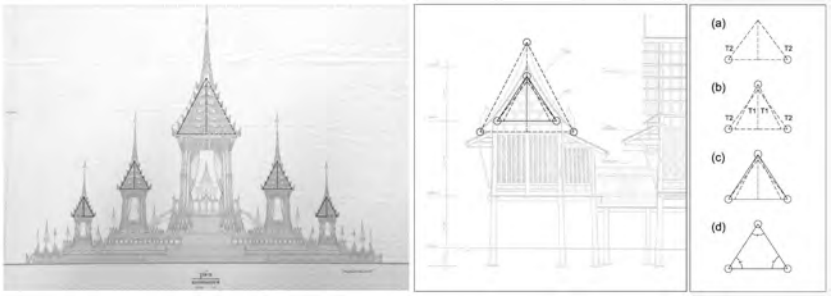


Figure 8. Left - An Analysis of the proportion of a traditional Thai structure using T1 (The blueprint of the Royal funeral pyre for the late King Bhumibol Adulyadej, designed by the Fine Arts Department). Right - An Analysis of a traditional Thai nobleman's house using T1 and T2.

Initially, the elevation view of the Royal funeral pyre for King Rama IX was traced. After that, two T1s, that were mirrored and of similar proportion to the main summit of thrones and the four sided posts, were rastered onto the drawing (figure 8-left). Then, a section of the Thai nobleman's house, including the external fascia board, was traced to analyse the roof's overall external shape. Finally, the interior structure was analysed by finding the pitch set by the internal rafters.

It was discovered that the overall roof pitch was similar to T1 at three important points where two units of T1 were mirrored. At first, the T2 angle was laid out against the base of the rafter, as shown in figure 8-right (a), and then T1 was placed proportionately on the centre line of T2, as shown in figure 8-right (b). It was noted that the top point of T1 and the two base points of T2 rationalised the shape and positioning of the internal rafters. This discovery may explain why Royal Thai Imperial Architecture features roof pitches that are steeper than are found in regular houses. The significance of the Kanok pattern to Royal Thai architecture may also be linked to the Western concept of the 'Golden ratio', which many aesthetic proportions are based on.

5.2. INTERIOR STRUCTURE

When the Kanok Sam Tua pattern's interior curves were investigated, it was found that they were linked to the main points of the interior structure. Additionally, it was noted that the pattern could be drawn using only two types of curves, (1) catenary and (2) Bézier. Therefore, it was presumed that the interior curves might have been based on the Fibonacci sequence. The initial results, using Rhino and Grasshopper's Fibonacci component revealed that the position of Kanok body 1 and Kanok body 3 were related to a Fibonacci series of 1 and 1.75. Accordingly, this relationship between the Kanok Sam Tua interior structure and Fibonacci numbers could be further investigated.

6. Conclusion and Discussion

This research has demonstrated that the process required to create the traditional Kanok Sam Tua pattern is structured and can be explained mathematically through geometry and visual algorithms. From the results, it can be concluded that Thai patterns can be accurately described using triangles and curves. Additionally, this research reveals that there is stochastic mathematical logic hidden behind the metaphorical Thai lotus bud design.

It is hoped that future studies would further interpret generative and shape grammar using software, such as 2d shaper, The Interpreter and 3d dynamic digitalised parametric inputs. Furthermore, software could be written for the parametric platform, which could generate new patterns based on the findings of this research. Finally, fabrication methods using bas-relief, or three-dimensional architecture could be explored in relation to this research.

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ENABLING CUSTOMER CHOICE IN HOUSING

Mass Customisation Solution for Prefabricated House Manufacturers

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Abstract. This paper presents a live and tested solution that enables home buyers to choose and customise their future homes in a web browser. It allows future owners and residents to configure and visualise their home in 3D but also keep it affordable by displaying the construction costs back to users in real-time. The proposed solution is analysed in the context of current housing market, excising web and BIM technologies and compared to currently available solutions. Additionally, we have been tracking visitor behaviour by using web analytics and can draw some conclusions about its performance.

Keywords. Mass customisation; housing; configurators; combinatorics; web technologies.

1. Introduction

With the invention of new web technologies in general and with the maturing of WebGL in particular it has become increasingly more feasible to build web applications that manipulate 3D geometry directly in web-browsers. This has created new opportunities for bridging the gap between buyer's needs to customise the design and efficient fabrication of new houses. The main value of this research lies not within the novelty of the subject area, but within the flexibility of the software architecture and suggested workflow as a generic solution for mass customising houses. We have established a scalable concept and direct workflow from desktop 3D modelling software via parametric software add-ons into a web-friendly format, allowing architects to present design options to the customer without the need of face-to-face consultation.

We have created a working online solution and have been tracking the use of our prototype solution using web analytics. Based on this we can draw some

conclusions on the end-user behaviour. More specifically, we are interested in finding the right balance between the freedom of end-user's choice and the ease of navigating the landscape of choice.

Although product configurators have become a common online sales and marketing solution, mass customisation of houses is fairly different from the personalisation of other products and is not yet used by manufacturers. Kendall (2013) points out that while the car industry is moving towards mass customisation, it is not a suitable model for housing as houses are tied to a specific location while the automobiles are particularly 'placeless'. Westerholm (2013) stresses that car industries and shoe manufacturers have introduced advanced web configurators because these they are operating with big volumes and can afford to invest into web technologies. Construction industry has been lagging behind because almost each project is unique and connected to its surroundings and cultural context. To date, there has not been a widely accepted workflow and software that makes mass customisation of houses possible.

We believe that our solution - although still in its early stage - can achieve scalability by giving individual architects the means to build online configurators. Empowered with appropriate tools architects will be able to offer automated choice for customers. The consequent shift in consultation and decision making process would epitomise the transformation of their role from being the designer of outputs (houses) towards being the designer of systems. Such kind of a transformation can be described both from the biologist's and the software engineer's perspective distinguishing between the creator of the "usable artefact" or phenotype and "the editable source code" or genotype (Fuller & Haque 2008). The paper argues that with the rise of prefabrication and mass customisation, customers will be given ability to configure suitable design solutions and architects simply need to provide the operational guidelines and content to enable it.

Already in 1980s Bernard Cache ja Gilles Deleuze suggested a distinction between 'object' and 'objectile' (Carpo 2011) in order to separate the mechanism of creation from the output. The objectile as opposed to an object, is an algorithm, which may determine an infinite variety of different objects. While this distinction makes a perfect sense in todays paradigm of parametricism, back then it remained an abstract concept without a concrete technical implementation. We find this distinction especially appropriate in order to describe the difference between a configurator and a configuration in the quest for defining mass customisation in prefabricated housing.

2. Demand for Mass Customisation in Housing

"The term mass customisation denotes an offering that meets the demands of each individual customer, whilst still being produced with mass production efficiency." (Piroozfar & Piller 2013)

Mass-customisation of houses can be seen as a blend of two strategies - mass production and individual customisation. While the latter is an age-old phenomenon, mass production can be attributed to the 20th century. More specifically, mass production strategies were invented after the Second World War in order to

rebuild societies and relieve housing shortages when existing construction methods could not meet the societal demands any more (Thuesen et al. 2013). While the mainstream construction industry in 1950s and 1960s aligned itself with the mass production and gradually become more streamlined in order to follow tight production and construction schedules, the early concept of mass customisation was also introduced to the public at the same time. In early 1960s Habraken (1972) proposed an alternative solution to the modernist mass housing that comprised of 'support' or a base building and 'infill' - a customisable fit-out.

In reality, mass customisation of houses has only recently started becoming a feasible construction method. While there has been a number conceptual works experimenting with the idea, the first real projects combining personalisation at the industrial scale and with industrial efficiency are surprisingly recent. This is perhaps not so much to do with technical possibilities, but can be largely attributed to the demand and market dynamics in general. For example, the current housing market in the Netherlands - the country that is undoubtedly one of the forerunners in adopting mass customisation in housing - is shifting towards a demand market instead of the supply market, as Dalhuisen (Zeist 2014) points out.

Housing trends in the Netherlands started pointing towards mass customisation in 1990s when some well-known examples of participatory design were brought into existence. While schemes like Borneo Sporenburg by West 8 in Amsterdam (Evans 2008) are not strictly speaking mass customisation examples, they have certainly paved the way to ones that have followed. In recent decades there have been a number of residential developments that are loosely adopting the concept of mass customisation as a marketing, design and construction strategy. One of the largest ones is Homeruskwartier in Almere, others include Palet van Delft, Wenswonen, Fenixlofts and many other smaller developments.

According to Oey (Zeist 2014) one of the reasons why mass customisation of housing is so popular in the Netherlands is because lot of Dutch people likes to build their own house which in turn has led to so called self-building movement. Same but perhaps more recent trends can be observed in the United Kingdom, where there is somewhat of a revolution undergoing in the housing sector in these years. Self and custom build is hoped to contribute towards solving the national housing crisis that has been ever deepening after mass production of modernist housing in 1970s. Similarly to Dutch people, a majority of home buyers in the UK are dreaming of building their own home. The Building Societies Association's survey (2012) found outr that "over half of all respondents (53%) said they would be interested in building their own home".

As a response, a number of new self and custom build developments have been granted planning permissions - the Heartlands regeneration scheme in Cornwall, Park Prewett development in Basingstoke and Beechwood West in Basildon, to name just a few. All of these feature a strong mass customisation element - future residents are given a choice to customize their home within the limits permitted by the architects, developers, local planners and house manufacturers. In fact, most of permissible house types are manufactured off-site which is also seen as a key measure to relieve the ongoing housing crisis in the UK.

There is a clear gap in the market that should be filled with an affordable

technology that connects customisation experience of the home buyer with the efficiency of off-site manufacturing into a seamless workflow. We shall refer to such a technology as house configurators. House configurators are 'objectiles' in deleuzian language. House configurators produce unique 'objects' or houses for the long tail of home buyers who don't like to live in a mainstream mass-produced home. Paraphrasing Anderson (2006) house configurators are tools for the future of business that allow selling less of more - they are aggregators of low demand products that collectively build a better market share than the best selling but un-customised houses

3. Online House Configurators

Web-based mass customisation technologies for housing have been researched and tested before. Some earlier examples include an interactive system for the design of customised housing by Duarte & Eloy (2000); Huang & Krawczyk (2006a, 2006b) and Huang alone (2007) have proposed a web-based questionnaire and a system to configure prefabricated houses. Typically, such attempts have stayed at the conceptual level and have achieved very little if any adoption by the industry.

In contrast to the aforementioned attempts YIT Stylemachine created by 3D Render (Westerholm 2013) has been actually used by the renown Finnish construction company. Stylemachine presents the end user an opportunity to customise generic rooms (e.g. kitchen, living room, bedrooms) with a set of predefined choices. Users can configure individual rooms but not the overall layout of the apartment. As the application is based on a set of pre-rendered images and image components, high visual quality gets preference over navigation and overall configurability. Similar applications to Stylemachine are in use in the Netherlands; Woonmodule and Palet van Delft (Zeist 2014) to just name few of these.

While there is clearly a 3D model or a set of models needed for creating such applications, they typically feature no real-time interaction between the user and the model. All choices offered to end-users are modeled in advance, in most cases also rendered and then uploaded for the user to browse.

However, recently a new type of building configurators has surfaced. In such configurators the user is actually interacting with 3D model guided by some quantitative information retrieved from the model in real time. For example, Studio Shed's Configurator (2016) is a good example where design customisation aligns with the production efficiency. Similarly to many online car configurators, this web solution is one-off configurator where the building (shed) model is tightly coupled with the customisation mechanism and the user interface of the system. In this respect Woonconnect (Sengers 2016) seems to be a more scalable solution. It is built on top of a digital library of building components provided by over a hundred different manufacturers. These components can be integrated with building applications and thus Woonconnect allows users to create new house designs.

4. A New Kid on the Block

The following sections in this paper describe a new online house configurator (figure 1) technology. We give an overview of its technical architecture, explain the

theoretical framework for the customer choice model and draw some early conclusions based on web analytics of the first 6 months after the launch in spring 2016.

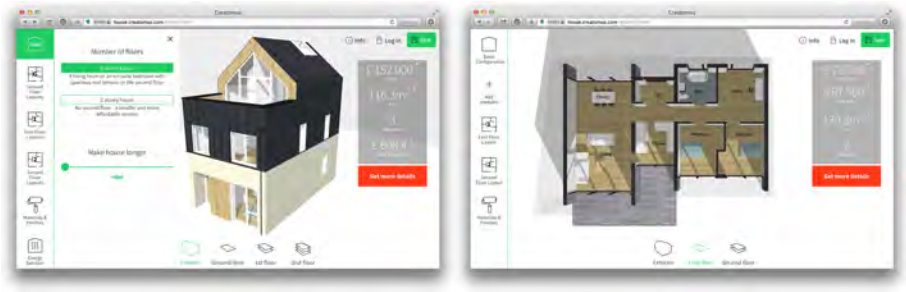


Figure 1. Screen captures of Creatomus' house configurator on https://house.creatomus.com/project/hta and https://house.creatomus.com/project/tube.

The house configurator technology was initially invented for enabling mass customisation of prefabricated private houses, but it can be adapted for other building typologies as well. The configurator is a web-based application that is intended to be easy and fun to use, yet guide home buyers through the decision making process of getting the house that they need and can afford to buy. It allows future owners to explore and configure the house in 3D while keeping an eye on the construction costs. While all design decisions are displayed in the interactive 3D model, the cost of each decision is immediately reflected in the total price for the selected design. Once the potential buyer is happy with the configuration, they can save the design for further communication with the manufacturer and the architect.

Home buyers are given the flexibility to customise general size and geometrical parameters (e.g. the size of windows, the pitch of the roof etc.) and layout options within the chosen house type. They can also explore different material variations and swap building products with alternatives ones. The design of a configurable house in general and all given design choices are conceptually organised into decision graphs. A simple decision graph would have a few plan layout options at each floor level and perhaps a couple of exterior finishes options leading to basic yet clearly presented choice model. More complex decision graphs can lead to a large number of different house configurations that are virtually impossible to reproduce using conventional CAD applications.

At the background, the application is connected to a web service that assembles 3D models by combining together elements designed by architects. 3D mesh geometry is manipulated in real time; the price of the house is also associated with the model geometry (e.g. floor area) and calculated near real-time. All design choices offered to the buyer are predefined but the final design is a result of combinatorics carried out according to the choice made by the buyer and as such is not predetermined. The modelling of designs choices is carried out in a CAD application (Rhinoceros), but the decision graph is knitted together online in a content management system. This separation of tools is yet another measure of increasing the flexibility and scalability of the system - new choices can be created and added

dynamically and previously created choices can recombined in order to assemble new configurable models.

5. Definition of the Configurable Model

A configurable model can be conceptually defined as a function or an algorithm that allows the user to change some given parameters. When the buyer's decisions are added to the configurable model, then the result is a defined architectural object or the configuration. The configurable model comprises all versions that the client can create by making different decisions. Principally the configurator and the configuration relate the same way as object and objectile as described by Bernard Cache (Carpo 2011): the configurator *objectile is an algorithm that can create several different outcomes; the configuration* object is one of the possible outcomes. Every configuration choice is comprised of options that the user can choose from. Presently, we have defined three types of choices on the basis of how they affect the architectural object:

- Choices of spatial alternatives offer different solutions in terms of floor layouts, number of floors, shape of the roof, etc.
- Choices of spatial transformations offer the user a way to manipulate the geometry by changing its geometrical parameters. Generally it can be used for changing the length and width of the house, the height of the ceiling, the pitch of the roof, etc.
- Choices of construction/product/finishing allow the selection of different materials, structural systems and building products. Generally these mean changes in construction but do not change the geometry of the house. The selection could for example involve exterior wall finishing, window types or other building materials (e.g. solar panels).

The decision graph architecture (figure 2) always has the root option of the model - a part that is visible to the user from the beginning. It is the starting point of the decision graph that has a reference to all first-level choices. In complex configurators, every option in a choice can have two types of information added:

- Sub-choices are choices that become unlocked once the user has made a decision for the parent option. This allows more complex decision graph of the configurator and offers a wider range of choices in a logical order.
- Semantic information - machine-readable information about the given choice, allowing the configurator to display numeric or other type of data; e.g. construction parameters, energy efficiency and price calculations. In the web interface this information can be extracted for all chosen model options in order to inform decision-making by summing up values for the bill of quantities or calculating energy efficiency based on the building geometry.

The critical question when implementing the decision graph architecture is to choose the most appropriate modelling paradigm. As mesh geometry does not contain semantic information, it is much easier to create choices: every object can be handled as an independent model and the simple action of pulling these models together leads to the final configuration. This would be far more complicated with BIM models since manipulating the model geometry the interdependencies

between different model elements would also need to be manipulated. On the other hand, if this problem was successfully solved, BIM would be a better option because the BIM-based models can be immediately used in the following design process.

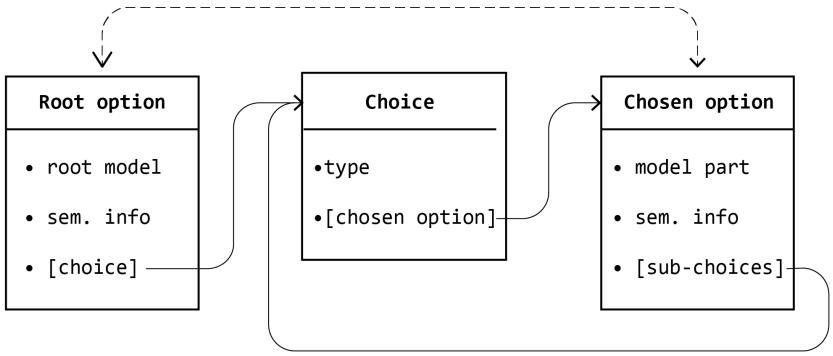


Figure 2. The decision graph architecture.

Nevertheless, our choice was to use mesh models. One of the main arguments is very pragmatic - spatial transformation choices are technically hard to implement in the currently available online BIM viewers (e.g. in Bimsync or Autodesk Forge Viewer) that do not support advanced manipulation of element geometries. Another reason is that users do not need to see and configure the entire BIM data. Therefore, it is technically more feasible to define partial models with relevant semantic metadata and deliver optimised 3D mesh representation to the web client. Mesh geometry can be created from almost any 3D representation of buildings and is thus a more universal medium. Plain mesh will have no parametric restrictions and rendering complexity like BIM element classes. Added technical and semantic descriptions and 3D rendering properties can be designed specifically for the configurator. Technical properties of partial models such as cost, heat loss or gain, number of bedrooms etc. that can be summarised and displayed as total figures for the chosen configuration. The downside of this approach is that the configurator will produce information for the web viewer only. Such a representation is not reusable in the further design process. This problem can be addressed with a separate backend tool that lets the architect or a backend service assemble the configuration in a desktop software format together with original CAD or BIM details (see section 7).

6. Learning from Users

One of the advantages for house manufacturers of using house configurators is the possibility of supporting product design, marketing and sales decisions on observable and quantifiable user behavior. Modern web analytics technology makes it feasible to significantly shorten the customer feedback cycle. In our case, the analysis of web visitors' behavior becomes an important driver in designing the

house configurator's decision graph. It is not only possible to observe an individual visitor's actions but also draw conclusions on the overall performance of design elements and identify popular design choices based on aggregated metrics.

We have carried out both qualitative and quantitative tests using our live house configurators. As our primary aim has not been to analyse any particular decision graph of configurator but the overall performance of the concept, all conclusions presented in this paper have been generalised. Qualitative usability test were carried out with a handful of users of which some were actually looking to buy a new house or were just recently done so, and a few casual web users. Quantitative tests were carried out with 133 people.

The interface of online house configurators was proven fairly intuitive and user friendly. Users managed to explore different views of the model and different design options easily. We found out that home buyers are indeed ready to focus on the task and even expect to concentrate because they are making important decisions about their future. It was found out that potential home buyers can handle 3D navigation such as rotating and zooming fairly well. While professional users (e.g. architects) are naturally more likely to navigate the 3D model by mouse, our initial doubts that people would not know how to explore 3D space were not grounded. Simple 3D navigation seems to be well within the capacity of a common web user.

One of the difficulties in using the configurator was finding a suitable camera angle for making certain design choices. Some users tend to click on design options that they cannot see - e.g. clicking on floor plan layout options when they are looking at the exterior view. Many users also failed to notice the total cost change when a new choice was selected. What seemed to take the longest time when using the configurator was understanding the difference between different design choices as presented in the configurator. Also, the real-time geometry changes in the 3D model were not always apparent - interaction with the interface that is detached from the 3D model seemed to be the culprit. It is suggested that choices should be somehow offered directly within the 3D model.

From the survey that was conducted after the quantitative test, we received some negative feedback about the clarity of graphics. However, it seems that the image quality was not an issue - even if everyone is used to high quality renderings, interactivity with the 3D models seems to compensate for the lower image quality. The biggest shortcoming of our current configurators is probably the number of design choices offered. Most of people get quickly used to the interface, but they also get quickly bored, if there is not enough choice offered.

7. Discussion: Beyond Simple Configuration

Zeist (2014) proposes a 5-stage process for mass customising houses in order to achieve truly personalised designs and form a user-centered design loop. This process includes the following stages: activity listing, activity descriptions, relationship diagrams, initial floor plan and final design. We offer a simpler workflow for involving clients into the design process. It comprises four stages:

1. An architect creates a configurable model using plug-ins in BIM/CAD software: options and chosen options with corresponding geometries and price calculations.
2. The model is uploaded to the web, ideally this stage would be automatic and only needs one click.
3. The client can access the configurator on the web and can make changes based on the options given by the architect and can get automatic live feedback about the geometry of the design, energy efficiency and price calculations.
4. When confirmed, the client's choices and comments are sent to the architect. The architect can access this data using a plugin, download them and recreate the configured model in the preferred design software.

This process should be cyclical: an architect creates a model, makes it accessible for the client and receives the client's choices and feedback. The workflow starts and ends with the architect and this gives the option to observe the stages in two groups: the 1st and the 3rd involves one of the parties (the architect or the client) either designing the model or making choices. The 2nd and 4th stage involve translating and forwarding data. The effectiveness of the workflow increases when the 1st and the 3rd step are handled in a single software platform. On the architect's side the model should be configured in the same BIM/CAD software that is used in their everyday design work. This functionality can be offered with plug-in software. On the client's side it should be a browser solution with no software downloads and installation.

When a configurable model is linked to the designing software in this way, it is fairly easy to use it as part of the design process in order to take narrative steps in designing and making relevant choices. Thereat the workflow is adjustable with many different user-scenarios. On one extreme it can be used for configuring finished designs that have many details and options. This could be applied for prefabricated houses that have been designed once and can be used over and over again; the user can choose among the solutions offered by the architect.

On the other extreme it can be used for fast communication between the architect and client in a standard design process: the architect creates a model that can be configured with a few choices, makes it available for the client, the client makes choices and the architect can add more detailed choices. This circle can be repeated as soon as new options become available. In addition these two workflows can be combined with each other. For example the user can choose a specific configuration from the reusable configurator and ask the architect to adjust it to the suit some specific needs.

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GENERATING URBAN FORM

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Abstract. Modern design of urban forms is venturing towards performative, site-specific architecture that are formed according to the attributes of its urban context. Parametric modelling techniques offer designers the ability to embed generative mechanisms into the design process to allow performance based design. This paper focuses on the development of a synthesis model that generates an Urban Form schema using computational design principles. The design system illustrates a rule-based systematic approach to urban form generation and is a precursor to the automatic exploration of urban forms based on design analytics and evaluation of urban metrics. The role of the architect begins to shift from the designer of objects to the designer of processes with urban planning following a trajectory of data-generated and contextual specific design.

Keywords. Parametric Modelling; Urban Modelling; Scripting; Urban Analysis.

1. Introduction

The design of modern urban forms is venturing towards performative, site-specific architecture that are formed according to the attributes of the urban context. A data-driven method of design is emerging where information regarding behavioural mannerisms and the urban context is embedded into modelling procedures and processes. Models are able to "reflect the complexity and dynamism of the systems with which they engage" (Barett et al. 2007). This evolution of urban type is directly associated with developments in Parametric tools as they permit the collection, storing and processing of vast amounts of data.

Parametric modelling provides the opportunity to automate the design process and quickly produce thousands of design forms that vary in spatial character. With scripting, designers have the ability to generate and select the most architecturally fit design outcome out of an extensive range of data-embedded, digitally generated alternates. Within this context, it is possible to pursue an evolutionary approach to urban design founded on the optimisation of design characteristics. An informal

urbanisation (Verebes 2014, pp. 17) is proposed where urban planning and the creation of urban space is developed according to "population thinking as opposed to typological thinking" (Verebes 2014, pp. 17). The result, is customised, site-specific architecture where the design embeds, and is a reaction to, the attributes of its surrounding urban context.

This paper presents the construction of a conceptual model that generates an abstraction of Urban Form using computational design principles. The model consists of a series of interrelated components that represent urban features including the Site, Transportation Network, Blocks, Plots, Buildings and Public Spaces. Each integrated component is reliant on the data gathered from its connected modules, with each module being a direct outcome of its linked predecessors.

2. Design System

Parametric modelling techniques offer designers the ability to embed generative mechanisms into the design process which result in a multitude of solutions that need to be assessed. Alfaris (2009) presents a framework for a multidisciplinary design system that describes how to decompose, formulate, model, integrate and explore designs computationally. A major aspect of this framework lies in the modelling phase which can be broken down into Synthesis, Analysis, Evaluation and Optimisation models. To produce a performative design system, a designer must be able to produce a synthesis model that outputs solutions. These solutions must be analysed, evaluated and optimised. Whilst each of these models are critical in the system, this paper focuses on the development of a synthesis model for generating urban forms, as the latter models are reliant on the initial synthesis model. A synthesis model abstracts design intentions into a collection of design parameters, rules or algorithms and can be constructed by parametric or algorithmic descriptions. This paper presents a synthesis model based on a design schema (Frazer 2001) that describes an urban form as a related network of design elements, namely Precincts, Road Network, Blocks, Plots and Buildings. The following section describes each element in more detail.

3. Urban Form System

The synthesis model described below demonstrates the generation of an Urban Form founded on a specific set of input data. The model is illustrated through a prototype tool that has been scripted in Python and visualised in Rhinoceros 3D to graphically illustrate an instance of a generated urban city block. The following components form the system.

3.1. PRECINCT

The precinct is the initial input driver for the system and defines the boundary of the urban site. It is represented by a 2D polygon and the initial shape and dimensions of the precinct have design implications for the next components. As part of the precinct definition, the designer can also specify global parameters about the design, including the number of road divisions, ratio of built environment to

parkland and range of building heights. The precinct is stored in the system and made available as an input to the Road Network module.

3.2. ROAD NETWORK

The Road Network is generated by firstly choosing an initial starting point along the Site Boundary. A line is drawn in the Normal direction from the original point and extended to the boundary line on the opposing side. An iterative process continues whereas each generated line is subdivided at a random point, with new perpendicular lines generated and extended until an obstacle is hit. This process is repeated until the number of iterations specified by the Precinct is complete (figure 1). The length of each projected line is maximised by the distance required to reach the closest obstacle. At each iteration, the linework is categorized as Primary, Secondary and Tertiary Road Segments. The result, is a network system that contains road segments of varying types.

Extending this notion further, an Offset tool is implemented where each road segment is offset by a specified amount according to the type of road. This offset amount can be varied manually by the user and results in Primary, Secondary and Tertiary Road networks with progressively smaller road widths (figure 2).

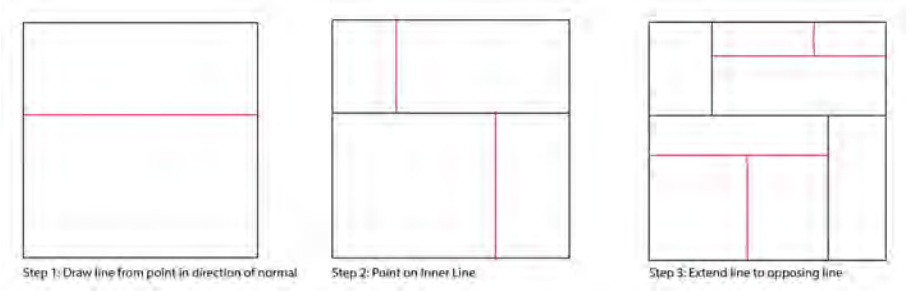


Figure 1. Road Network Process.

3.3. BLOCKS

The next module, Blocks, is derived directly from the Road Network. The Road Network segments are used to split the Site Boundary area into a series of street Blocks. As the road widths are automatically generated using the offset function described earlier, the blocks are created taking into account the physical space of the road network (figure 3). The Block sizes are determined and limited to the space remaining between each road segment. The size of each block can be determined by the initial user-defined percentage input into the system as the user is able to define the number of road divisions and ratio of built environment to parkland and can ultimately gain control over the range of block typologies. The individual blocks provide information on the size of each block, their location, surrounding road network, proximity to one another and so on. The benefit of this is that this data can be used to determine the function and use of each block. For example, blocks that are long and thin could be split to create smaller roads between the two longer edges.

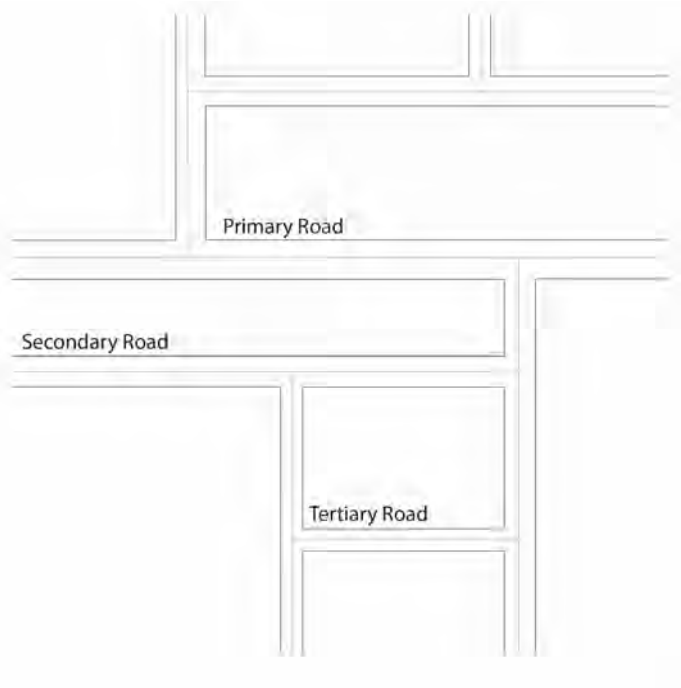


Figure 2. Road Network Hierarchy.

3.4. PLOTS

With the blocks now constructed, they can be subdivided into a series of plots. The strategy for subdivision is determined by the type of block, the dimensions and available area. The blocks are split into three categories: Parks, Residential and Commercial. Based on the type of block, it is subdivided into a series of smaller plots to host a variety of building forms. The designer is able to define a specific percentage of blocks they wish to be residential and commercial as well as the maximum and minimum heights they require for each building. This is achieved by firstly assessing the width and depth dimensions of each block. If deep enough within the constraints of the block type, the block can be split using a centre line through the mid-point of the smaller side of the block. This centre line is then divided into equal spacing and lines are drawn from each divided point in the direction of the normal to the opposing boundary line to form plots. Variations in the block subdivisions can be seen in figure 4. Variations in the park to building form can also be seen in figure 5.

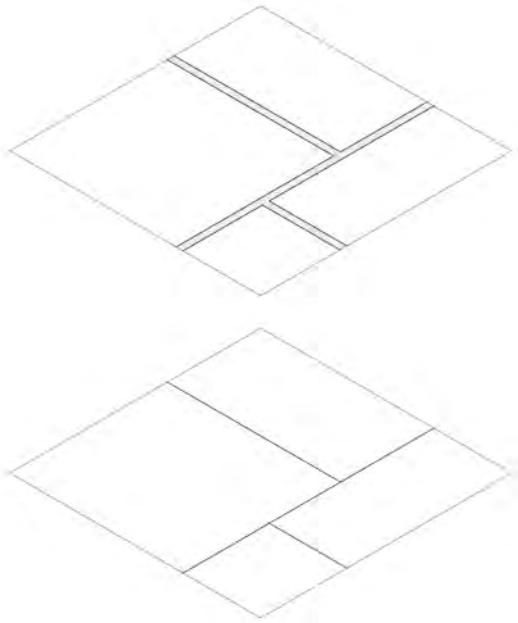


Figure 3. Splitting of Blocks using Road Network.

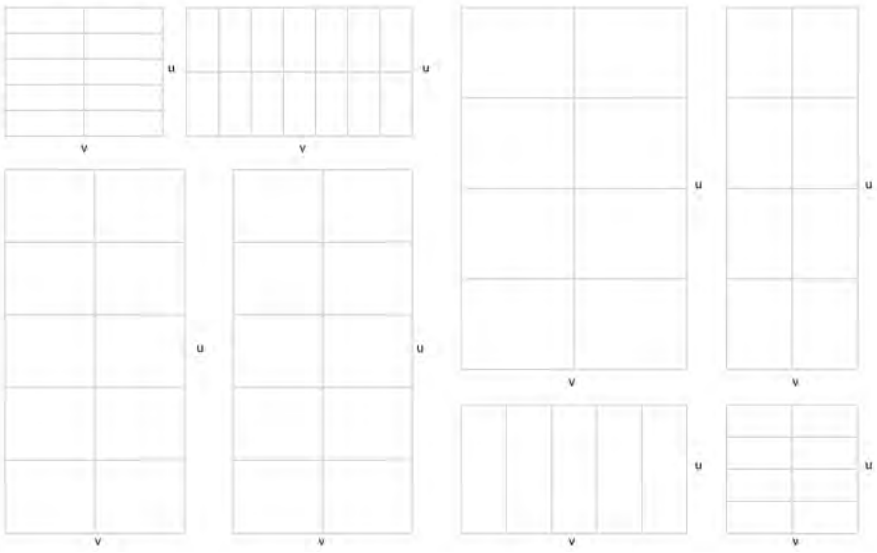


Figure 4. Plot Subdivision.

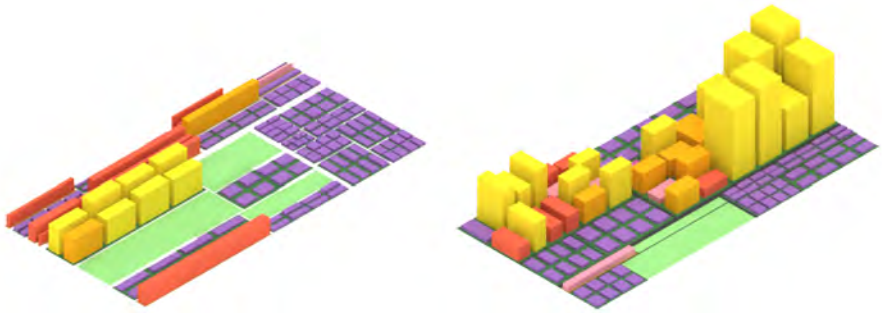


Figure 5. Changes in park to building percentage.

3.5. BUILDINGS

The system now contains individual plots, an area-driven offset tool, and a parameter to determine the minimum and maximum height of each building. These parameters are able to be varied by adjusting a number in the Python script. By changing the number range of the parameters, the user is easily able to manipulate the size, shape and overall form of each design variation outputted from the system. In this design system, the buildings are represented as simple extruded masses to give an indication of the urban character (figure 6). As this is an independent module in the system, it can be refined and enhanced to produce more detailed generated building forms in future research. At a later stage, a Grasshopper component could be implemented into the system to improve the accessibility of the project parameters for the user. Rather than manipulating the parameters through a Python script, they can be represented as a plugin in Rhinoceros in a manner that visualises the variables simply.

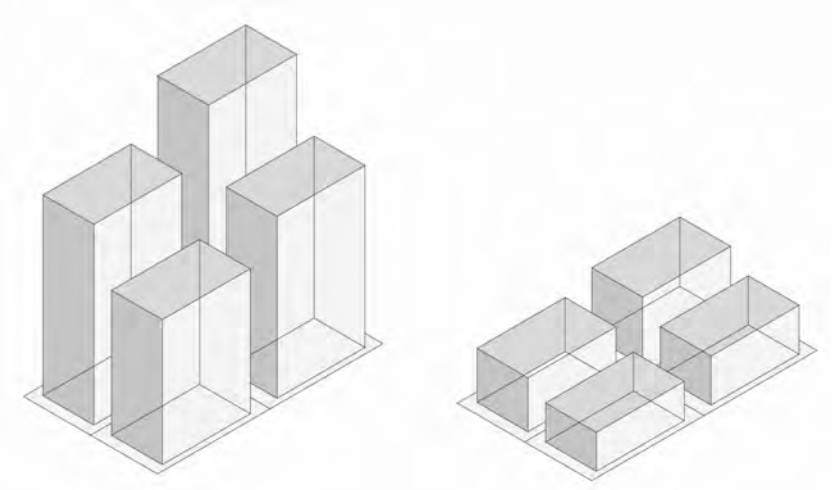


Figure 6. Building offset tool.

4. Implications for Urban Design

The design system illustrates a method for generating complex urban networks through a parametric approach based on a series of rules and parameters. It proposes a "clear rule-based systematic approach to form generation" (Knapp 2014, pp. 42) and therefore possesses the ability to automate the design process by quickly generating forms founded on urban design schema and user input. Each element of the Urban Design system is separated as an individual component and therefore begins to break down the current perception of urban form. As a result, users have the option to accurately design each aspect of the Urban Form system separately. Each component relies on its predecessor for information and input data and therefore the overall form is founded on the combined data of each individual component. The role of the architect begins to shift from the "designer of objects to the designer of processes" (Knapp 2014, pp. 42) with urban planning following a trajectory of data-generated and contextual specific design. Each element of the design system is modularised and is open to development and variation in design logic. The result of the Urban Generator system is evident as even within a single design schema, a multitude of design options can be generated by modifying the input parameters (figure 7).

It becomes evident that computational design techniques offer new methods to "reflect the complexity and dynamism of the systems with which they engage" (Barnett et al. 2007). These revised methods permit the profession to extend their design capabilities by offering a new medium to present building information that is "characterised by dynamic change" (Belesky et al. 2015, pp 196). With the development of this synthesis model and the flexibility it offers in designing the conditions required to generate urban form, it becomes possible to review and manipulate concept designs at an early stage of production. The parametric model permits the simulation of a range of dynamic building forms that emulate a variety of urban design scenarios. The benefit, is that it reduces the amount of time taken to form, document and analyse each concept design. Using this system, the design process can be improved as it allows the assessment of a greater set of design options in a short amount of time. Improvements to design concepts are palpable as generated forms are now created off user and contextual-based data using this parametric system. Urban design data that has previously been difficult to obtain and implement into a design is now available and easily integrated into concept designs, giving designers the ability to test, assess and generate numerous contextually-relevant forms.

In addition to this, further urban design forms can now be generated using analysis, evaluation, and optimisation modelling. Architects and designers gain access to rigorously test urban design options without the burden of having to represent and manually model each individual design. The use of automation is therefore favoured as it "significantly accelerates the design process by front-loading key design decisions about composition and performance, while also significantly reducing the effort required to represent the resulting decisions" (Belesky et al. 2015, pp 199).

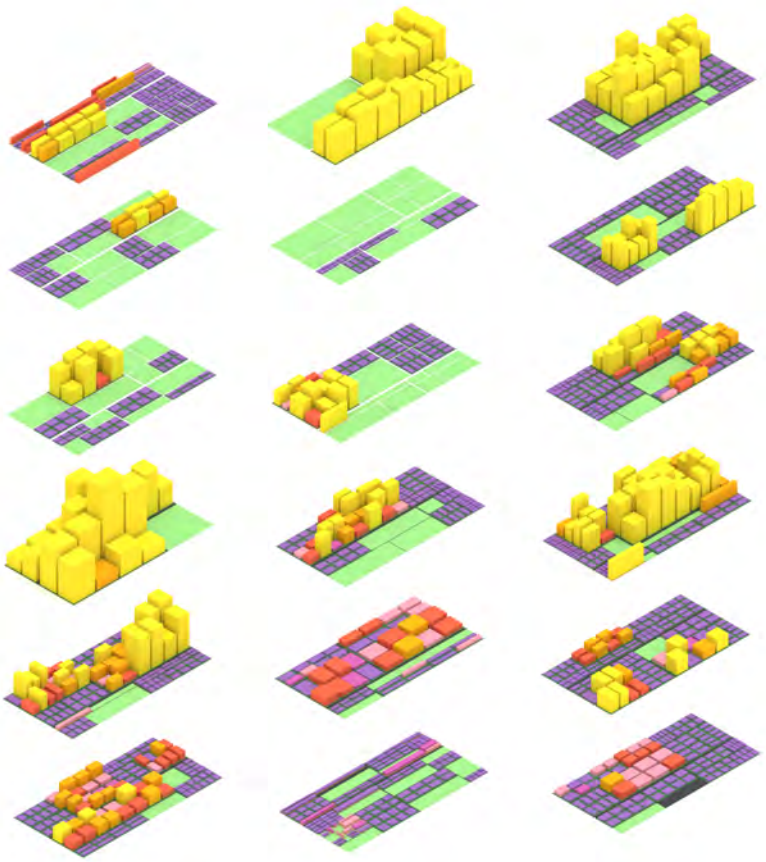


Figure 7. Iterations of generated design outcomes using the synthesis model.

5. Future Work

Further research would involve exploring and developing related urban design models and using the associated data to enhance and complete the performance design system. Creating analytical models would allow data and associated metrics to be extracted and stored in a database that can be assessed in a larger context. The type of data metrics available would include common metrics such as FSR, Building Heights, Population, Density, Size and Public Space areas amongst others. This would then allow for evaluation and optimisation models to be constructed, facilitating an iterative, performative process that results in an array of urban forms. The design space gains flexibility and is easily manipulated. Following this, designers are able to pursue an alternative role in the architectural field. Rather than focusing their time and efforts on manually testing design iterations, the automated process associated with parametric design allows them to focus on design optimization and performance.

6. Conclusion

It becomes evident that data driven methods of design are shifting the field of architecture from that of repetitive building techniques to performance-driven design where data is able to be extracted from digital models and implemented both as an analytical tool and as a method for evaluating architectural designs. Digital design becomes a form-finding process where evaluative criteria drives the design process itself. The benefit of this, is that each simulation is able to be tailored to its surrounding urban parameters such as existing plots, road layouts, streets and so on. The design system demonstrated in this paper is an example of how urban form can be generated with its data extracted and used further to create performative architecture. Having the ability to generate vast amounts of urban forms through computational design techniques offers an advantage to the architectural field as designers are able to focus on assessing and evaluating their designs rather than performing monotonous modelling tasks.

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Design Optimisation

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OPTIMISING HUMAN COMFORT IN MEDIUM-DENSITY HOUSING VIA DAYLIGHT AND WIND SIMULATION

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Abstract. This paper explores the pedagogical context for the inclusion of daylight and wind simulation as part of architectural design-studio teaching. The author describes both challenges as well as opportunities encountered by architecture students who applied high-end technology for optimizing environmental conditions during the conceptual design of a residential project within a thirteen week studio. Students located their projects in an inner urban context in a 'Temperate' climate zone, meaning that they had to account for hot conditions in summer while considering wind-chill factors in winter. Based on the studio experience, the paper scrutinizes how students tackled Computational Fluid Dynamics (CFD) and daylight analysis on different scales of their project. The paper explores how the engagement with latest tools available to architecture students changes their ability to discuss building physics with engineers and question precedence typology. The author describes the pedagogical challenges when helping architecture students to overcome obstacles in communicating engineering aspects inherent to the design process.

Keywords. Environmental Analysis; CFD; Daylight Simulation; Design Pedagogy; Parametric Design.

1. Introduction

Advancements in daylight simulation and computational fluid dynamics (CFD) offer educators unprecedented opportunities to include environmental performance feedback in their teaching. Until recently, the application of CFD analysis was at arm's length for most architecture students. It has been calculus-intensive and reliant on bespoke engineering software. In addition, CFD analysis tools often required a steep learning curve to master and students experienced delays in receiving feedback due to the response-time required to carry out calculations. Today, computational means to analyse environmental performance is becoming more accessible and 'real-time'. A number of questions associated to this new-found freedom arise when considering design pedagogy: How can CFD and daylight analysis

be integrated within a semester-long design studio? What is the desired level of accuracy of analysis for design decision support? What is the desired knowledge-level of architecture students regarding building physics (and the associated analysis tools)? How can educators empower students to critically reflect on analysis outcomes and use results effectively to facilitate design changes? What level of interaction with engineering experts benefit architecture students in order to verify the validity of their analysis and design decisions? And finally, do CFD and daylight analysis make students less dependent on design based on precedent typologies by offering them alternative solutions that can be tested instantaneously? The author ran a thirteen-week Masters-level design studio at the Melbourne School of Design in order to tackle the above questions. The paper offers a brief review of approaches to daylight analysis, and it introduces the tool applied for wind analysis as part of the studio. In addition, this investigation reflects on the interaction students had with an engineering expert who offered targeted advice on environmental concerns during the second half of the semester, thereby scrutinizing the extent to which architecture students can/should engage with environmental analysis as part of their design process. The paper offers insights about the extent to which architecture students can most purposefully take their building sustainability exploration, complement their design-thinking, and prepare them for informed conversations with their engineering counterparts.

2. Methodology and Approach

The findings presented in this paper draw from two approaches of inquiry:

1. A literature review of selected papers that report on past efforts in applying computational analysis for testing the effects of daylight distribution and wind/natural ventilation on human comfort in an academic setting.
2. A critical account of the pedagogical approach towards teaching current daylight and wind simulation software as part of a reference project developed by a group of Masters-level architecture students at the Melbourne School of Design.

The key interest of the author was to understand the characteristics of applying latest technology for wind and daylight testing as part of conceptual design in a semester-long studio setting. Compared to previous efforts in the field, what are the opportunities that present themselves to designers who apply daylight and CFD analysis as a matter of course in their early stage design process? The Design studio was subdivided in three phases. From week one until four students dedicated their time on site analysis, including an in-depth study of the prevailing climatic conditions on site throughout the year. In this first phase students developed their preliminary building morphology based on both environmental factors, as well as social aspects of cohabitation and social interaction in a medium-density housing setting. In order to achieve the above students spent the first four weeks of the semester in groups learning about the principles behind CFD and solar/daylight analysis. It was pivotal for students to be able to tie their investigation about environmental performance back to urban planning constraints as well as human experience, behavior and comfort levels. The second phase from week five until nine was dedicated to fine-tuning and advancing design proposals individually. That

phase included iterative processes where students frequently went back and forth from analysis to update their design and verify validity of their assumptions both on a qualitative (aesthetic/social) as well as quantitative (plot ratio/daylight exposure and wind-scenario) level. The third phase form week nine until thirteen resulted in detailed optimization of facade articulation in conjunction with apartment layout and the integration of (semi-)public spaces and circulation. The diagram in figure 1 highlights a process chosen by a student in the use of environmental analysis that spans from an urban scale to a precinct environment and ultimately to the apartment layout.

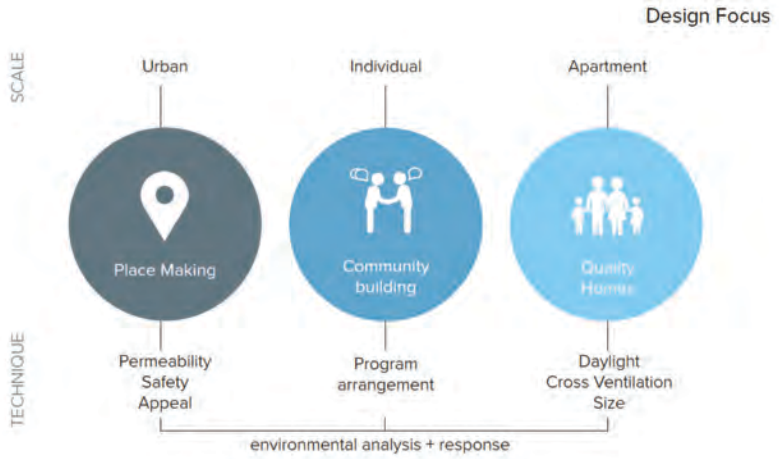


Figure 1. Process articulation based on the three key areas of investigation.

3. Background

The application of computational means for assessing environmental conditions in architectural and urban design has advanced steadily over the past three to four decades. Initially relegated to a peripheral aspect of architectural design-education, and often carried out via custom scripts and experimental software applications (Maver 1987; Maver and Petric 1995), environmental analysis has moved ever more central-stage. In addition, environmental performance guidelines and associated building codes have led to an ever-increasing use of applications for assessing urban micro-climates as well as building sustainability by architects and engineers. Upon review of existing literature, three key developments become apparent. Firstly, environmental analysis get increasingly applied in early stages where designers still juggle with rapid changes and incomplete information (Den Hartog and Koutamanis 2000). Secondly, advancements in analysis tools allow users to simulate environmental performance of their design ever more accurately without depending on heuristic methods (Fraser and Donn 2011). And thirdly, the increasing proliferation of environmental analysis applications hand in hand with the integration of these tools with existing parametric modelling and topology optimization applications, allowing - in some cases - for multi-criteria optimization across different environmental analysis domains (Sheikh and Gerber 2011;

Kaushik and Janssen 2012). Despite the advances mentioned before, the proliferation of various types of environmental analysis into the design studio has not occurred uniformly. Drawing on ten years of studio teaching where environmental analysis formed a pivotal part of the design process the author could observe that tools associated to sun-path analysis, solar gain, daylight performance, or even carbon-footprint have seen the highest uptake by students. High levels of uptake are due to the relative low level of complexity and computing power required to carry out calculations. For these types of analysis, energy performance results can be mapped onto building topology in a graphically explicit manner by a large number of design tools (Ecotect (TM), IES (TM), Ladybug (TM) & Honeybee(TM)). In contrast, the calculus-heavy approach for measuring the impact of wind via CFD poses much higher performance requirements on computer hardware, in addition to requiring more expert knowledge on how to set up the boundary conditions and how to interpret simulation outcomes.

3.1. DAYLIGHT SIMULATION WITHIN THE ARCHITECTURE CURRICULUM

The availability and quality of natural daylight is an important factor associated to human comfort in residential design. Being able to predict and regulate daylight access in residential design and to test compliance against local regulations has become a crucial component of architectural design. The simulation of daylight is an advanced application of solar analysis. It is based on ray-tracing algorithms that determine daylight (luminescence) factors drawing on exposure to solar gain taken from artificial sky conditions. RADIANCE (Ward 1994) is one of the most commonly applied applications for validated lighting simulation; and it integrates with a great number of design modelling/analysis applications. Hanna (1996) reports on early attempts to integrate daylight analysis software with commonly used CAD tools, highlighting the benefits of using photo-realistic renders for teaching architecture students and practitioners about the use of daylight enclosed spaces. The effects of student learning experience through daylight simulation has been addressed in greater detail by Almaiyah and Elkadi (2014) who report on the relevance of careful integration of technical aspects within design studio teaching. They highlight the need for group work, expert feedback and verification to avoid for the analysis part to become self-referential. An example of daylight distribution on an apartment floorplan carried out in McNeel's Rhino/Honeybee interface can be seen in figure 2.

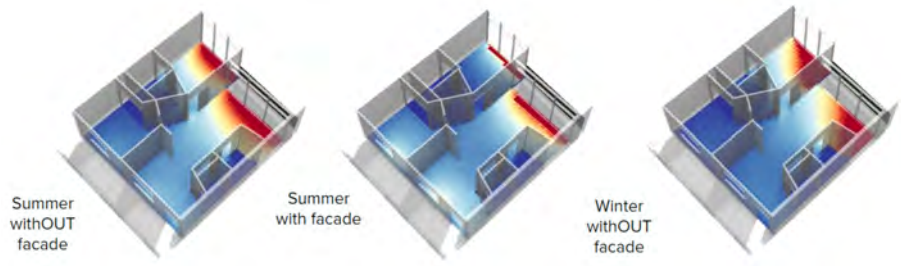


Figure 2. Daylight distribution on apartment floorplan based on season and facade variations, image A.Clemens.

3.2. CFD FOR WIND ANALYSIS IN THE ACADEMIC DESIGN STUDIO

A number of researcher have studied the application of CFD for supporting early-stage architectural design. Den Hartog, Koutamanis and Luscuere (2000) focused on indoor climate analysis in their quest for software applications that help the bridge the gap between design analysis and synthesis using CFD tools. They see the 'formalization of design experience in base cases' as a pivotal means to facilitate the definition of solution types, thereby simplifying access to analysis results. The accuracy of CFD tools in comparison with physical wind-tunnel testing gets interrogated by Moya et al. (2013) who assess their usefulness for small-scale architectural interventions (wind-shelters) in an urban context. The findings presented in their paper highlight the usefulness of such studies in support of architectural design-decision making. Looking at wind-flow on an urban scale, Kaushik and Janssen (2015) report on means to diminish the time required to carry out CFD analysis via two predominant means: Solution Approximation and Solver Approximation. Whereas the former relies on the transformation of 3D geometry into 2D representations (and therefore lacks the accuracy required for simulation in an urban/architectural context), Solver Approximation shows more promise for scenarios typically encountered in architectural design. Drawing on feedback within existing literature, the author has applied a recently developed tool that promises to overcome some of the challenges typically encountered when using CFD analysis in a quickly changing early-design context. With the tool Flow Design (TM), the software company Autodesk (2014) has released an application that is suitable to approximate CFD for wind analysis on both an urban as well as an architectural scale. The characteristics of Flow Design(TM) include a user interface that requires minimal input from designers who quickly want to explore preliminary - early stage - options for their projects.

4. Reference Project - Master's level Design Studio

When setting up the program for the reference project presented here, the author was able to draw on prior experience in implementing environmental analysis as part of an architectural design studio (Holzer 2008; 2015; 2016). Feedback from these efforts highlight some key challenges when integrating a strong analysis component with the design process:

- The need for students to first engage with basics of environmental analysis
- A steep learning curve by students associated to learning environmental analysis tools
- Understanding what to measure and determining the level of accuracy of analysis
- The clarity of results allowing architecture students to interpret building physics behaviour
- The students' ability to verify and discuss analysis outcomes with engineers
- The ability to question building typology that's based on precedence due to alternative solutions emerging from analysis.

In a 13-week design studio setting it is pivotal to allow students to focus on design rather than being sidelined by steep learning curves for tool-uptake and technical

analysis. The focus of the studio therefore was on place-making with a strong emphasis on human interaction and comfort. Students were tasked to develop a proposal for a medium-density residential project in an inner-urban setting. Environmental analysis was a supportive component of this effort. It was introduced on two levels:

1. as part of the optimisation of the urban microcosm of a medium-density residential project; there the focus lay on optimizing climatic conditions of public spaces
2. as part of the design and layout of residential apartments, in terms of their orientation, solar/daylight access as well as cross-ventilation opportunities within each apartment

The exemplar project was located in the town of the author's home institution where a moderate climate with cold winters and hot summers is prevailing. One particular climatic condition at the location is the change in wind direction between winter and summer. In order to study this wind condition, students set up their project's geometry parametrically so to be able to quickly adjust orientation and building height in the early conceptual stages of their project. This flexible setup lent itself to preliminary testing of sun-hours exposure of individual apartments. For CFD analysis, output from their parametric models was then combined with the surrounding urban context model and exported into Flow Design(TM) to check for wind-performance. Figure 3 shows an example of early-stage wind-analysis based on differences in summer/winter wind directions in Melbourne.

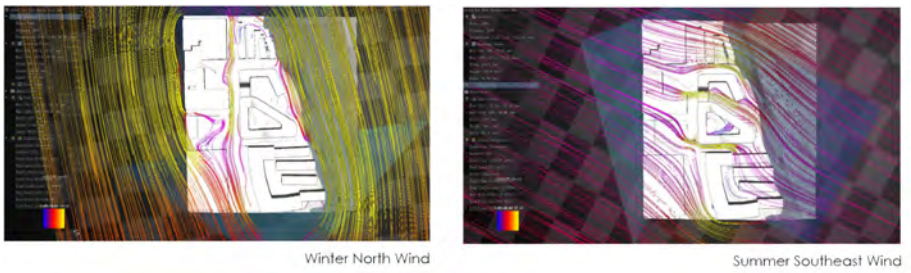


Figure 3. Seasonal differences in prevailing wind direction, image by Jinhui Zhu.

5. Discussion

Reflecting on the studio outcome as well as the process leading up to its completion, a number of observations can be made about the students' use of wind and daylight analysis as part of their exploratory design process.

5.1. ENGAGING WITH THE BASICS OF CFD ANALYSIS IN THE STUDIO SETTING

Feedback gathered during the case-study design studio highlighted that the limited knowledge about building-physics by architecture students and the lack of knowledge about the correct setup of virtual wind-tunnel boundary conditions can lead to incoherent results when using CFD in support of the design process. When it

came to articulating solutions for the urban context, students needed to test and understand the impact of wind-direction on the building typology, orientation, and morphology of their design. Whereas animated wind-breezes in the warm season were welcome, students needed to find ways to adjust their project's morphology in a way that would allow them to block out unwanted wind-gusts in winter. The wind-chill factor is a major impediment to human comfort in open/public spaces and it needed to be considered as part of the urban design element during the semester. As for daylight analysis, students were quick to realize the basics of daylight distribution, but they struggled to work towards specific targets.

5.2. CFD SOFTWARE LEARNING CURVE EXPERIECED BY STUDENTS

In contrast to the author's prior experience related to CFD software uptake by students, Flow Design's pre-set environment for wind testing allowed users to master its key functions within days, if not hours. One major reason for the quick engagement with Flow Design is due to the great number of pre-set physics and calculus parameters. They allow users to focus on analysis itself without requiring in-depth knowledge about specific physics benchmark. As an example: A parametric setting within Flow Design constrains the relation between the boundary size of the area to be solved and its voxel grid-size, thereby limiting the time required for any given analysis run.

5.3. LEARNING WHAT TO MEASURE (AND HOW ...)

All 16 students participating in the studio struggled initially to grasp what exactly they should measure when it comes to assessing environmental performance. As much as they were quick to set up boundary conditions for simulation and get going with analysis runs, when probed about the exact purpose of their investigation, they could only refer to vague assumptions of what it is they were testing. Students first needed to learn how to associate qualitative aspects of human comfort to quantitative parameters inherent to and stemming from analysis. It took most at least two to three weeks to get a grasp on key benchmarks to work towards, either relating to desired wind-speeds and behavior, or related to luminescence factors at a certain depth of the floor-plates of their apartments (figure 2).

5.4. INTERPRETING RESULTS

Depending on the level of detail desired for CFD output, calculations took between 2-4 minutes before 'live' flowline diagrams and flow-vectors were used to display the analysis results. Whereas architects are trained to question design decisions and to detect flaws in their conceptual approach, they are not equally trained to scrutinize results from building performance tests. It could be noted that at the start of the semester students often followed the principle of: 'what looks right may as well be right', leading to confirmation bias and skewed results. The students' inability to critically reflect on simulation output was one of the key obstacles in the effective use of CFD in the design studio.

5.5. INVOLVEMENT OF ENGINEERING EXPERTS TO HELP VALIDATE RESULTS

In order to counter the effects of confirmation bias, the studio was sets up to include industry-experts with engineering background who would engage with students face to face to go through their projects at regular intervals throughout the semester. That way, confirmation bias could be eroded over time as the engineers explained in more detail who results from wind analysis needs to be interpreted and what benchmarks to work towards. Three such feedback sessions throughout the semester led to an increase in understanding for students to advance the CFD-related aspects of their design. Once students were confident about the validity of results, they were able to step back and analyse the articulation of their facade solution in a holistic fashion, addressing desired views, regulating daylight access, and providing options for natural ventilation. At the final crit each student presented provided a well-argued-for outcome highlighting how they incorporated feedback from CFD and daylight analysis in their final design (both an on urban as well as architectural level). The crit-panel included an environmental engineer who was probing students on this aspect.

5.6. SCRUTINISING PRECEDENCE VIA THE APPLICATION OF CFD AND DAYLIGHT ANALYSIS

Morphology of medium-density housing projects traditionally often result from typologies that draw on precedence. One major goal of the case-study design studio was to test to what extent CFD and daylight analysis can reduce a designers' dependence on precedence typology and allow them work on alternative typologies with confidence. All students were encouraged to start of their environmental analysis based on basic geometric blocks (with various scale and orientation) to then conduct wind and solar analysis on well-known residential typologies (tower/block/etc.). The next step was to move away from these known typologies and introduce variations that maintained functional relations, while exploring unprecedented building morphologies. In that sense precedence served as a stepping stone for a more flexible, experimental setup, supported by immediate performance feedback facilitated via CFD and daylight analysis. During the course of the semester, students progressed from a focus on typology and morphology towards a focus on the building-skin definition. Students used analysis results from both CFD and daylight simulations to inform their parametric setup of window sizing, louver-system geometry and the positioning of balconies. Figure 4 illustrates how CFD was applied on this detailed level in order to maximize air-intake for cross-ventilation based on predominant summer-winds.

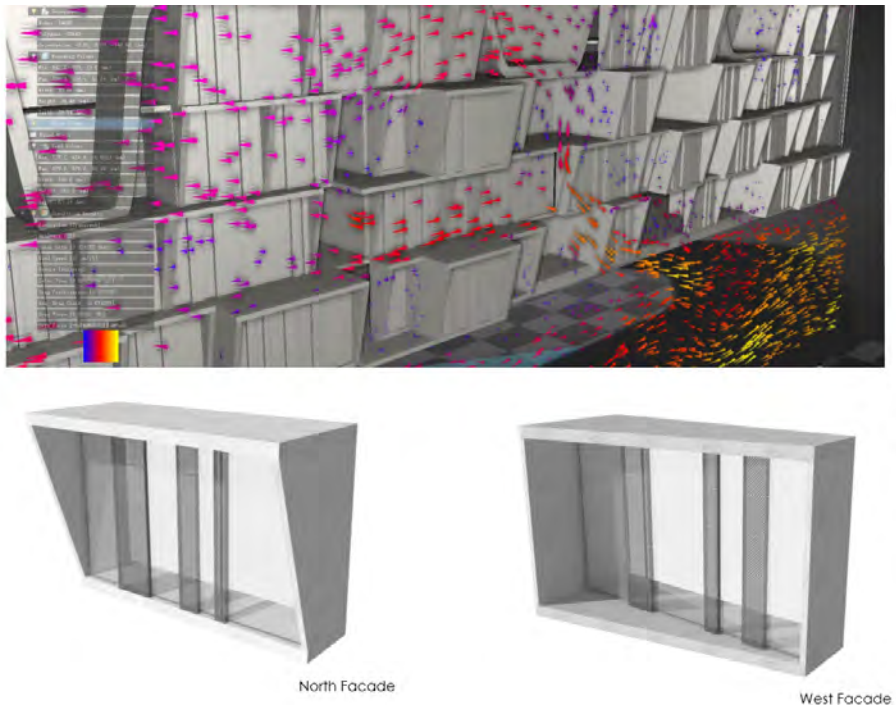


Figure 4. Facade options based on Wind studies, image Jinui Zhu.

6. Conclusions

Reflecting on the author's 10+ year experience in applying environmental analysis in an academic design studio settings, the current suite of computational tools assisting daylight and wind analysis represent a major step forward. Optimizing human comfort in consideration of daylight and wind is increasingly becoming accessible to architecture students with no or little prior knowledge about building physics or associated tools for testing aspects of it. Existing literature highlights the advancements in software application over the past two decades. As shown on the exemplar project, the use of tools such as Grasshopper/Honeybee(TM) and Flow Design(TM) has become 'second nature' to students in due course of a 13-week design exercise. The major step forward for daylight analysis is the opportunity to link parametrically defined geometry directly to solar/daylight simulation, thereby avoiding time-consuming re-modelling when creating multiple options for testing. As for CFD analysis, it is mainly the availability of sufficiently precise near-time solvers that approximate the otherwise calculus-heavy and lengthy CFD process. Observations during the exemplar project highlight the need for educators to monitor tightly how students apply boundary conditions for simulation and how they interpret results from analysis runs. In addition, it is essential for students to be able to tie physical building performance to social behavior and human comfort. Understanding the often complex interplay between people's behaviour and their

built environment under varying climatic conditions (both indoor and outdoor) is pivotal to the successful design of medium-density housing. One major obstacle for efficient CFD testing of various design options remained the lack of fast CFD (approximation) solvers that integrate with parametrically set up geometry. At the time of writing this paper, such as solution (Butterfly) is seemingly being developed for McNeel's Rhino/Grasshopper software environment, but thus far, students still had to rely on 'one way' software exports of their Rhino/Grasshopper models into Flow Design for further analysis. With this obstacle hopefully removed in the not too distant future, students should be able to speed up their virtual analysis of wind behavior in a parametrically defined setting.

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OPOSSUM

Introducing and Evaluating a Model-based Optimization Tool for Grasshopper

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Abstract. This paper presents Opossum, a new optimization plug-in for Grasshopper, a visual data-flow modelling software popular among architects. Opossum is the first publicly available, model-based optimization tool aimed at architectural design optimization and especially applicable to problems that involve time-intensive simulations of for example day-lighting and building energy. The paper details Opossum's design and implementation and compares its performance to four single-objective and one multi-objective solver. The test problem is time-intensive and simulation-based: optimizing a screened façade for daylight and glare. Opossum outperforms the other single-objective solvers and finds the most accurate approximation of the Pareto front.

Keywords. Design Tool; Architectural Design Optimization; Model-based Optimization; Sustainable Design.

1. Architectural Design Optimization

This paper presents Opossum, a new optimization plug-in for Grasshopper, a visual data-flow modelling software popular among architects. Opossum is the first publicly available (from www.food4rhino.com), model-based optimization tool aimed at architectural design optimization (ADO) and especially applicable to problems that involve time-intensive performance simulations of for example day-lighting and building energy. Such simulations play an increasingly larger role in architectural design processes and were for example employed by the designers of the Louvre Abu Dhabi (Imbert et al. 2013). Model (or surrogate)-based optimization methods find good results with small numbers of simulations (Holmström et al. 2008; Costa & Nannicini 2014; Wortmann & Nannicini 2016). This high speed of convergence is important for sustainable design problems such as daylighting and building energy, where a single simulation takes several minutes or hours to complete. In such cases, it is impractical to perform the thousands of simulations required by population-based metaheuristics such as genetic algorithms (GAs). But

model-based methods are rarely used in ADO (Evins 2013). Grasshopper and other architectural, parametric design software such as Dynamo (Asl. et al. 2015) and DesignBuilder (Singh & Kensek 2014) come equipped with only metaheuristics. Opossum fills this gap by making model-based optimization available to a wider audience and accessible to non-experts.

1.1. GLOBAL BLACK-BOX OPTIMIZATION

Simulation-based optimization problems define the relationship between variables and performance objectives not with an explicit, mathematical function but by evaluating a parametric model with numerical simulations. This relationship often exhibits local optima and complex, non-linear dependencies between variables. Global black-box (or derivative-free) optimization methods do not require a mathematical formulation and therefore are particularly appropriate for simulation-based ADO problems. Such methods balance establishing an overview over the design space with focusing on a promising region of the design space to find the best solution. There are three categories of black-box methods: (1) Direct search, (2) model-based methods and (3) metaheuristics. Global direct search and model-based methods alternate between global and local search, while metaheuristics limit an initially global search to an increasingly local one as the optimization progresses.

1.1.1. Direct Search

Direct search methods evaluate design candidates in a deterministic sequence. The Hooke-Jeeves and Nelder-Mead Simplex algorithms (Nocedal & Wright 2006) are classic examples of local direct search algorithms. DIRECT (Jones et al. 1993) is a global direct search algorithm that recursively subdivides the design space into hyper-boxes. This paper tests the implementation of DIRECT in the free, open-source NLopt library (Johnson 2010).

1.1.2. Model-based Methods

Model-based methods employ surrogate models (explicit estimates of the implicit mathematical formulations of black-box problems) to guide the search for good solutions. Trust region methods (Nocedal & Wright 2006) employ local models, while more recent, global model-based methods model design spaces completely. Global methods construct models with a variety of statistical (e.g. Polynomial Regression and Kriging) and machine learning-related (e.g. Neural Networks and Support Vector Machines) techniques (Koziel et al. 2011). Opossum, the optimization tool presented here, approximates the design space using radial basis functions (Gutmann 2001). Surrogate models accelerate optimization processes, since they are much faster to calculate than the underlying simulations. Approaches that completely replace time-intensive simulations with surrogate models (e.g. Yang et al. 2016) and then apply optimization methods are limited by the models‘ initial precision. Increasing the models’ precision requires a larger sample size, which can negate the initial speed advantage. Contrastingly, model-based methods iteratively build and refine models during the optimization process. One

optimization steps consist of (1) searching the model for a promising solution to evaluate, (2) simulating the found solution and (3) updating the model based on the simulation results. In this way, model-based methods continuously increase the model's accuracy. The ten runs of the model-based algorithm in the benchmark below each constructed and updated a surrogate model from 200 simulated solutions. In testing the accuracy of these models against all 10.200 solutions simulated during the benchmark, the maximum deviation was 53% of the true objective value, but the mean deviation was only 11% of the true value. Global model-based methods are particularly effective for optimizing problems with costly evaluation-for example time-intensive simulations-and complex relationships between variables and objective (Holmström et al. 2008). This effectiveness, combined with opportunities for visualization and interaction afforded by the surrogate model, makes model-based optimization attractive for ADO (Wortmann et al. 2015). Opossum, the optimization tool presented here, provides an easy-to-use interface to RBFOpt (Costa & Nannicini 2014), a state-of-the-art model-based optimization library. In the 2015 GECCO Black-Box Competition, which considered 1.000 mathematical benchmark problems with two to sixty-four variables, RBFOpt ranked first among the open-source solvers (Loshchilov & Glasmacher 2017).

1.1.3. Metaheuristics

Population-based metaheuristics (Talbi 2009) start with randomly generated populations of design candidates that they improve heuristically. Unlike direct search and model-based methods, metaheuristics do not rely on mathematical proofs of convergence but draw their inspiration from natural processes, such as genetic evolution or "swarm intelligence". Due to this lack of rigor and poor performance on benchmarks (Rios & Sahinidis 2013; Costa & Nannicini 2014), the mathematical optimization community regards metaheuristics as "methods of last resort" (Conn et al. 2009). Nevertheless, metaheuristics are the most popular category for ADO, and GAs the most popular algorithm (Evins 2013). This popularity is due to a relative ease of implementation, a wide availability, and a perception that metaheuristics are especially appropriate for complex problems with multiple optima (e.g. Attia et al. 2013; Evins 2013). This paper tests implementations of single- and multi-objective GAs and of particle swarm optimization (PSO) and simulated annealing (SA).

1.2. PARETO-BASED OPTIMIZATION

Multi-objective optimization aims to find good values for more than one performance objective. The problem in this paper considers daylight and glare, but combines the two into a single objective by subtracting them from each other. In other words, it defines an a priori weightage between daylight and glare. Pareto-based, multi-objective algorithms, which often are GAs, do not define such weightages, but instead try to satisfy all objectives as much as possible. Often, there is a tradeoff between objectives: e.g. allowing more daylight into a room can lead to more glare. Pareto-based optimization illuminates such tradeoffs by searching for non-dominated solutions, i.e., solutions where improving one of the objectives is only possible by worsening others, and graphing them on the Pareto front. Compared to

single-objective optimization, Pareto-based optimization is a less established field, with a smaller number of algorithms, proofs of convergence and experimental results. However, it nevertheless is popular in ADO (Evins 2013). Radford and Gero (1980) suggest an affinity between the numerous tradeoffs addressed by architectural design and the smaller number of objectives addressed by multi-objective optimization. But Pareto-based optimization is less efficient than its single-objective counterpart since the former focuses on finding not only good solutions, but also on achieving a good spread of solutions on the Pareto front. In the benchmark of a building energy problem with two objectives by Hamdy et al. (2016), it took 1400-1800 function evaluations, i.e. simulations, for the Pareto fronts to stabilize. To explore this efficiency difference, this paper compares five single-objective algorithms with the multi-objective HypE (Bader and Zitzler 2008). It evaluates HypE's performance as a single-objective algorithm and compares the Pareto front found by HypE with the fronts found implicitly by the single-objective algorithms. Extensions of model-based methods to Pareto-based optimization exist: Knowles (2006) recalculates a single surrogate model with different weightages at every iteration. Akhtar and Shoemaker (2016) employ one surrogate model for every performance objective.

2. Opossum: a New Model-based Optimization Tool

RBFOpt is programmed in Python 2.7 and relies on libraries for numerical computations (NumPy and SciPy) and auxiliary optimization (Pyomo). But Grasshopper supports only IronPython, a Python variant integrated with Microsoft's .NET framework that does not support these libraries. Opossum is written in C#, which Grasshopper supports. The C# program starts an external Python 2.7 process that runs RBFOpt. Opossum and RBFOpt exchange data via a (hidden) command line window.

2.1. ALGORITHM PARAMETERS

RBFOpt has more than 40 parameters, some of which are interrelated and some of which dramatically change its behavior. One can choose between two model-based algorithms: Gutmann (2001) and MSRSM (Regis & Shoemaker 2007). For global search, Gutmann evaluates the surrogate model's point of largest curvature, based on the assumption that this point yields a large improvement of the model's accuracy. MSRSM searches the model for points that balance improving the model's accuracy with the promise of better solutions, using either a genetic algorithm, random sampling or mathematical solvers. There are five choices of interpolating radial basis functions (linear, multi-quadratic, cubic, thin plate spline and automatic selection), which result in models with varying accuracy depending on the optimization problem.

2.2. OPOSSUM GUI

To make this complexity accessible to non-experts, Opossum's GUI consists of three tabs that afford increasing levels of control (figure 1): (1) The first tab lets users choose between minimization and maximization, select one of three pre-sets

of parameters, and start and stop the optimization. The pre-sets (Fast, Extensive and Alternative) are based on intensive testing with mathematical test functions. "Fast" runs MSRSM with a genetic algorithm. "Extensive" is identical, but spends more time on searching the model. "Alternative" runs Guttmann, which works well in certain cases. The first tab also displays an animated convergence graph to inform users about the progress of the optimization. (2) The second tab lets users define stopping conditions based on the number of iterations or the elapsed time, and to conduct and log multiple optimization runs. (3) The third tab accepts command line parameters for RBFOpt. When desired, this "expert" window gives the user full control, with the parameters entered here overriding parameters set by the first two tabs. In Grasshopper, Opossum follows the look and behavior of existing optimization tools, including conventions regarding the colors of optimization components and their connections to variables and objective values (figure 2). Double-clicking on an optimization component opens a window with a GUI unique to each tool, which, for Opossum, contains the three tabs discussed above. Opossum thus presents a complex and innovative optimization library in a manner that is easy-to-use and familiar to users of Grasshopper.

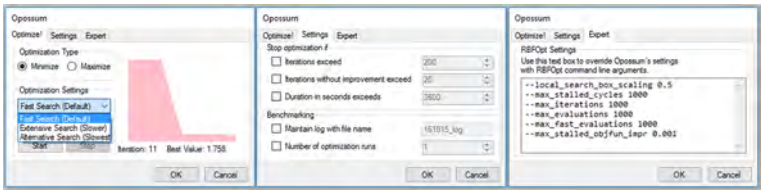


Figure 1. The three tabs of Opossum's GUI, from left to right.

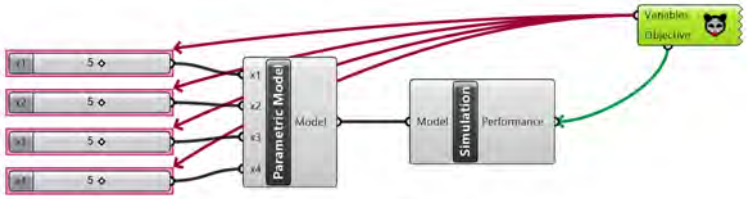


Figure 2. Opossum in Grasshopper. The curves on the left link to the variables and the one on the right to the objective.

3. Evaluation

To evaluate RBFOpt and Opossum, we compare its performance with five other solvers available in Grasshopper: the GA and SA included in Galapagos (Rutten 2010), the PSO of Silvereye (Cichocka et al. 2015), the DIRECT algorithm included in Goat and HypE included in Octopus (Vierlinger 2013). We test the solvers on a time-intensive, simulation-based problem: optimizing a screened façade for daylight and glare. We simulate daylight and glare with DIVA-for-Rhino 4.0 (Jakubiec & Reinhart 2011).

3.1. EXAMPLE PROBLEM: OPTIMIZING DAYLIGHT AND GLARE

We consider a single room in Singapore (figure 3). The rectangular room has a South-facing, 10.8 meter-long and 3.6 meter-high façade, and is 7.2 meters deep. The room's floor is raised 20 meters above the ground level. For the façade, we propose a porous screen with a triangular grid of 1.692 circular openings. To avoid controlling every opening with an individual variable and to create a graduated, cloudy appearance, a grid of forty "attractor points" controls the openings, with weights in the range [0.0, 1.0]. To create a soft falloff, we calculate the radius of every opening as the average of the values of all attractor points, weighted by the inverse cubes of their distances to the opening and multiplied by the maximum radius of 65 millimeters. Openings with a radius below 10 millimeters are closed completely. This formulation results in a problem with forty continuous variables.

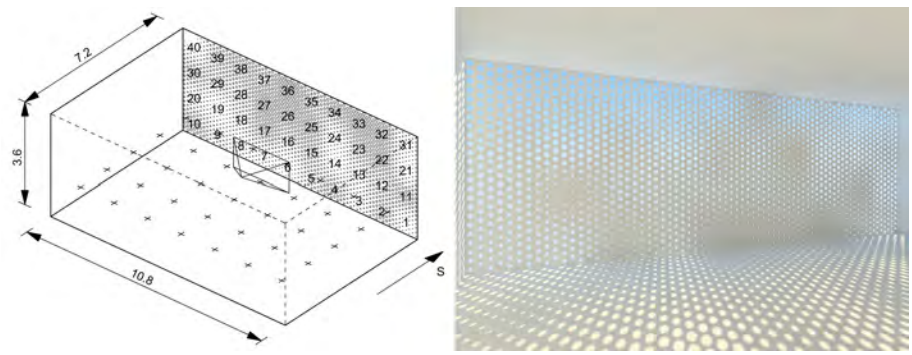


Figure 3. Diagram of the room being optimized in terms of daylight and glare. The numbers from one to forty indicated the positions of the attractor points, the crosses the sensor grid for simulating UDI and the cone the camera position and view for simulating DGP. The visualization on the right represents the best solution found, with 86% UDI and 24% DGP.

The objectives of the optimization are to (1) maximize Useful Daylight Illuminance (UDI) while (2) minimizing Daylight Glare Probability (DGP). UDI measures the annual percentage of time that a sensor point receives an amount of daylight that is sufficient for office work while avoiding glare and excessive heat gains (300-3000 lux). This problem calculates UDI as the average from a seven by five grid of sensor points. DGP measures glare as a percentage for a specific camera view and for a specific point-in-time. This value indicates whether the glare is imperceptible (35% > DGP), perceptible (40% > DGP ≥ 35%), disturbing (45% > DGP ≥ 40%) or intolerable (DGP ≥ 45%). We calculate this value for a single camera. The south-facing camera points directly at the screen and is in the center of the room at a height of 1.6 meters from the floor. An annual glare simulation calculates direct sunlight only for the daylight hours of five days (21th of June, August, September, October and December). In Singapore, these days add up to 59 daylight hours. For the remaining hours in the year, the simulation interpolates the direct sunlight contribution. Nevertheless, annual glare simulations can take hours even at low quality settings. This time-intensiveness makes such simulations impractical as an optimization objective, especially for the repeated runs necessary

for benchmarking. Instead, we approximate annual glare as the average of the 59 DGP values corresponding to the 59 daylight hours on which the more extensive annual glare simulations rely. Although less accurate than a full annual simulation, this approach yields a good qualitative assessment of the amount of glare one would experience in the room. If quality of daylight and avoidance of glare are equally important, subtracting (approximated) average annual DGP g from average annual UDI u yields a single maximization objective (both UDI and DGP are in the range $[0, 1]$). We turn this result into a minimization objective by subtracting it from 1.0:

$$\min f(x) = 1.0 - \overline{u}(x) + \overline{g}(x) \tag{1}$$

On an Intel Xeon E5-1620 CPU with eight threads and 3.6 GHz, one evaluation of this objective, i.e. generating the parametric geometry and performing the daylighting and glare simulations, takes about 90 seconds.

3.2. BENCHMARKING METHODOLOGY

We compare the results of the six solvers (DIRECT, RBFOpt, GA, SA, PSO and HypE) from ten runs with 200 function evaluations. To make the results independent from computing speed and implementation details, we compare the solvers in terms of the number of function evaluations, rather than in terms of running time. In practice, compared to the time required for function evaluations, running time differences between solvers often are negligible.

We run all solvers with default parameters, except for the GA and HypE, where we reduce the population sizes to 25 to achieve a larger number of generations. Choice of parameters can have a significant impact on the performance of optimization algorithms, especially for metaheuristics (Talbi 2009), and is problem-dependent. Nevertheless, we assume that the authors of the tested solvers have chosen sensible default parameters. Furthermore, in practice there usually is a limited evaluation budget, which is better spent on using solvers that are efficient out-of-the box than on tuning algorithmic parameters.

We compare the solvers in terms of two criteria: (1) speed of convergence and (2) stability. Speed of convergence refers to how fast algorithms approach the optimum, measured as the improvement per function evaluation. Stability refers to the reliability of optimization algorithms and is a concern especially for stochastic algorithms such as metaheuristics. One measures stability by applying statistical measures such as standard deviation to the results of repeatedly running an optimization algorithm on the same problem. We compare the Pareto-based solver with the single objective ones by calculating single objective values for the solutions found by HypE with the weighted objective function (formula 1). We compare the single-objective solvers with HYPe by recording individual UDI and DGP values. Plotting the non-dominated solutions allows a visual comparison of the Pareto fronts found by the six solvers in terms of the quality and spread.

3.3. RESULTS

The convergence graph on the left in figure 4 depicts the average, current best value found by the solvers relative to the number of evaluations. DIRECT is the

worst-performing solver and shows little improvement because its recursive subdivision proceeds too slowly in the forty dimensions corresponding to the variables. (DIRECT tends to show better performance on lower dimensional problems (Wortmann & Nannicini 2016).) SA performs relatively poorly, while the remaining metaheuristics, including the Pareto-based HypE, perform similarly and improve the objective by around 40%. Opossum's RBFOpt is the best-performing solver with an improvement of 50%. Note RBFOpt's rapid progress after 40 evaluations: Here the algorithm starts profiting from the surrogate model, while the earlier evaluations sample the objective function with a quasi-random Latin Hypercube Design. The box plot on the right in figure 4 indicates the range of objective values found by the solvers in five runs. DIRECT is fully deterministic. Of the remaining algorithms, RBFOpt is the most stable, with the single-objective metaheuristics displaying wider, less stable ranges.

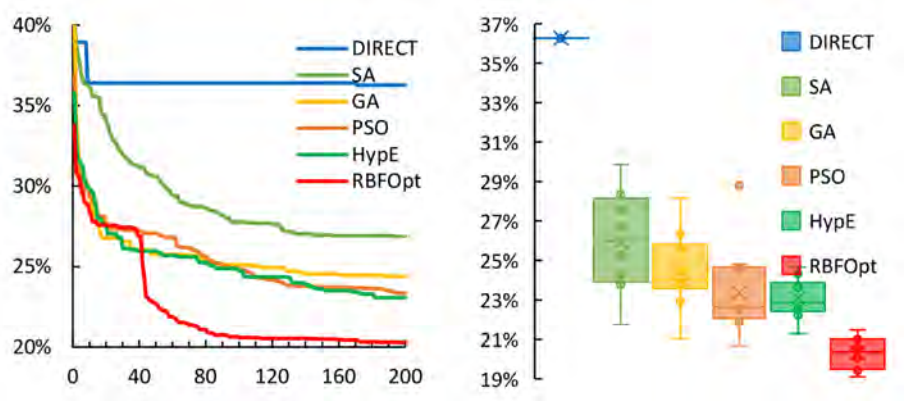


Figure 4. The convergence graph on the left displays the number of function evaluations on the x, and the average objective value on the y axis. The box plot on the right indicates the range of objective values found by the six solvers in ten runs. .

In figure 5, RBFOpt and HypeE have found the closest approximations of the Pareto front. The diagonal fronts indicate a tradeoff between maximizing daylight and minimizing glare, although large improvements of daylight quality can be achieved by accepting small increases in glare. (Note that low average DGP values can contain isolated instances of disturbing or intolerable glare.) This improvement is especially noticeable for RBFOpt: It finds high-daylight solutions that also suffer less glare than the next best daylight solutions by other solvers. HypE suggests a steep tradeoff between daylight and glare, while RBFOpt indicates that the tradeoff is less dramatic.

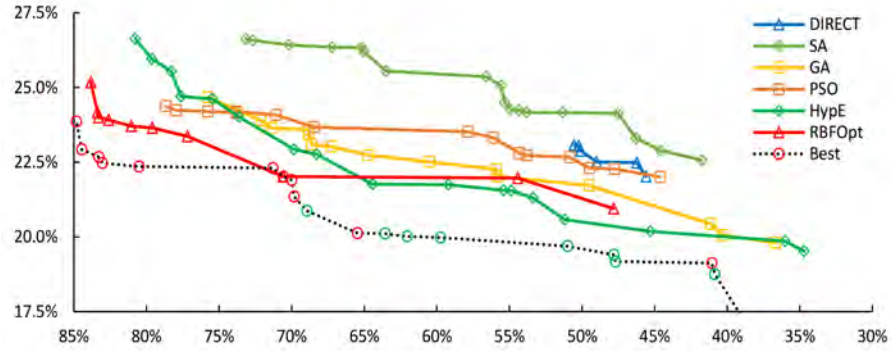


Figure 5. Pareto fronts found during each solver's most representative run. "Best" is the combined front from all solvers and runs (The markers' color indicates the solver). UDI indicated on the x-, and average DGP indicated on the y-axis.

4. Conclusion

We have presented a clear example of a time-intensive, simulation-based ADO problem that benefits from model-based optimization. Although algorithmic performance is problem-dependent, Opossum's RBFOpt is the best choice when the evaluation budget is small. The comparison with a Pareto-based algorithm indicates that, as a single-objective algorithm, HypE performs similar to other metaheuristics. But the single-objective RBFOpt finds the closest approximation of the Pareto front, especially for high-daylight solutions. Designers should thus employ multi-objective optimization judiciously and only when a large evaluation budget is available to avoid an inaccurate approximation of the Pareto front. The future development of Opossum will aim to make it more visual and interactive, following the ideas outlined in (Wortmann 2017). Another direction is to support Pareto-based optimization.

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A MULTI-OBJECTIVE GENETIC ALGORITHM FRAMEWORK FOR EARLIER PHASES OF ARCHITECTURAL DESIGN

A Case Study

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Abstract. This paper presents an algorithmic framework proposal for implementation of a multi-objective genetic algorithm (MOGA) in architectural design process. Different than the previous studies, we introduce a dynamic and extendible modular framework for multiple objectives. The objective modules with different fitness functions are connected simultaneously in the Rhino/Octopus interface, after multiplication with a constant value or a variable. In this study, we discuss the potentials and limitations of MOGA in 3D form generation, implications of MOGA in a case study and the qualitative and quantitative changes in relation to the change of constant value/ the impact ratio of competing objectives. The outcomes of the case study are investigated based on its potentiality in providing feedback in the earlier phases of decision processes in design.

Keywords. Multi-objective; genetic algorithm; architectural design process; case study.

1. Introduction

Complexities in natural systems have been a source of inspiration for researchers throughout centuries, whereas some resulted with well-established theories and concepts. The change in the distance between the theoreticians and ongoing interactions of the nature, in other words, the tension between the theory and the observed reality, gave rise to both the emergence of divergent conceptualizations and their different interpretations in different disciplines. Being derived from the theory of evolution, genetic algorithms (GAs) may be considered as one of the nomadic concepts which gain different explanations in different contexts. Following John Holland's first introduction of a genetic algorithm concept in 1970s (Goldberg & Holland 1988), and John Frazer's (1995) extension of the boundaries of the

concept of evolution in 1990s, it has become a well established approach today in architecture with an acceleration in the last two decades. New tools, methods and approaches have emerged in parallel to the usage of GAs in the architectural design process. Apart from the studies in which GAs are defined by the usage of low level computer programming, there are many software packages and their add-ons available for the implementation of Gas today. The wide-ranging adaptation of genetic algorithms (GA) in architectural design is mostly focused on combination of two initial genotypes based on the definition of a fitness function. However, simultaneous evaluation of multiple and competing goals might have potentials to provide a rich population domain, besides usage of mutations. As De Landa stated, a virtual evolution process becomes a useful exploration tool only if it can provide emergent and shocking outcomes (De Landa 2002). In this sense, multiple objective genetic algorithms with a changing and non-dominated fitness function might be more crucial for future implementations of GA in architectural design. In the scope of this study, GAs are assumed to be not only a singular approach, but also a way to integrate many approaches to create a hybrid system. We recommend going back one step in the formulation of GAs and merging the multiple competing goals of the selection process. This paper aims to introduce a framework proposal for a multi objective genetic algorithm (MOGA) and its implications in a case study. The proposed MOGA algorithm framework contains static and dynamic modules such as regulations, environmental condition analyses as static, designer-specified goals, and domain-specific goals based on building types as dynamic modules. The modules listed above with different fitness functions are simultaneously connected in the Rhino-Octopus interface, after multiplication with a constant value. In this study, we will discuss the potentials and limitations of of MOGA in a 3D form generation, implications of MOGA in a case study, and the qualitative and quantitative changes in relation to the change of constant value, namely the impact ratio of competing objectives.

2. Genetic Algorithms in Architectural Design

Genetic algorithms (GAs) are search, selection and optimization methods, which were first developed for machine learning and optimization problems (Beasley et al. 1993; Rosenman 1997). Historically, earlier implementations of GAs in architectural design were seen in well-defined design problems or optimization processes. Reaching Bentley & Wakefield's (1997) indication of the potentials of GAs in the conceptual design process, various methodologies and new ways of thinking in different contexts have emerged. However, despite a growing engagement of architects with GAs, today, a deep gap still exists between the non-linear nature of design and the strictly defined structures of GAs. In other words, there might be difficulties in approaching the well-defined and ill-defined design problems simultaneously. Here, the terms well-defined and ill-defined refer to Hayes' (1978) and Ormerod's (2005) definitions for problem-solving strategies. Non-dominated sorting algorithms have a potential to partially respond to providing a shared ground for evaluation of different goals simultaneously.GAs are capable of solving multi objective optimization problems. A single objective GA have a potential to be adapted into multi-objective algorithms to find a pool of non-

dominated solutions. The concept of non-domination is related to taking more than one solution in the selection process, which allow the survival of recessive genes apart from the best solutions. The advantage of non-domination in GAs is its focus of enrichment to the diversity of solution space, in contrast to the singular solution search of standard GAs. As Bandyopadhyay & Saha (2013) stated, in their experience, dominance or degradation of one objective to others resulted with closer outcomes in real-life problems. They added that, non-dominance might be crucial for fields such as "product and process design, network analysis, finance, aircraft design, bioinformatics, the oil and gas industry, automobile design, etc. (Bandyopadhyay & Saha 2013). To briefly mention other studies, implementation of pareto optimization to design solutions was introduced in the early 1980s (D'Cruz et al. 1983). Although the usage of GAs in multi objective optimization problems has increased in the last decade, the first MOGA was submitted by Schaffer was called Vector Evaluated Genetic Algorithms (VEGA) (Schaffer 1984). After that study, several multi objective evolutionary algorithms were developed including Multi-objective Genetic Algorithm (MOGA) (Fonseca 1993), Niched Pareto 6 Genetic Algorithm (Horn et al. 1994), Random Weighted Genetic Algorithm (RWGA) (Murata 1995), Nondominated Sorting Genetic Algorithm (NSGA) (Srinivas & Deb 1994), Strength Pareto Evolutionary Algorithm (SPEA) (Zitzler 1999), Pareto-Archived Evolution Strategy (PAES) (Knowles & Corne 2000), Fast Non-dominated Sorting Genetic Algorithm (NSGA-II) (Deb 2002), Multi-objective Evolutionary Algorithm (MEA) (Sarker et al. 2002), and Rank-Density Based Genetic Algorithm (RDGA) (Lu & Yen 2003). There are many variations of multiobjective GA in the literature, the cited GAs are the most known that have been used and tested in many studies.

3. A Framework Proposal for Multi-Objective Genetic Algorithm

A dynamic modular framework proposal for a multi objective genetic algorithm (MOGA) is shown below (figure 1). It contains static and dynamic modules such as regulations, environmental condition analyses as static, designer-specified goals, and domain-specific goals based on building types as dynamic modules. In figure 1, the gray colour represents whether the module and sub-feature were used in the case study. The white colour in the background of the modules represent the potentialities of the framework; however the modules were not examined yet. The number of the modules and sub-modules, the parameters and level of detail might change according to the context and scope of the design problems. The modules are considered to be changed, updated or manipulated by users depending on the design requirements. Moreover, the weight ratio of each module can be also changed by users.

The regulations module is a context-depended module that is specific for the case study. In the zoning regulations sub-module, there are pre-defined parameters provided by municipality. Solar analysis is selected as one of the physical environmental parameters. The domain specific design goal may change from one design problem to another, however, in the case study the decisions on the relations of the functions such as residential and leisure usage are taken into consideration. In relation to the designer specified goal module, a series fitness functions were

defined and used such as site efficiency control based on comparison of the void-solid ratio, the attraction point based height definition. As discussed in the next section, at least one sub-module for each module is selected to test the potentials of the introduced framework.

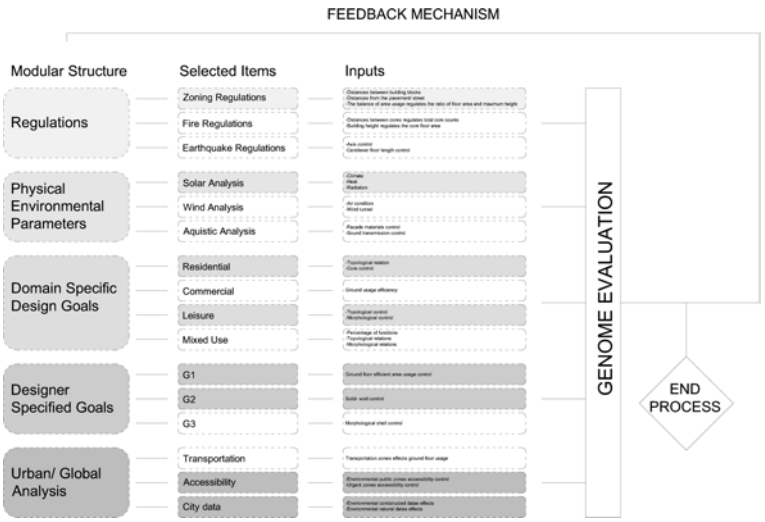


Figure 1. The algorithmic schema of the proposed MOGA.

4. Mixed-Used High Dense Housing as a Case Study

The case study involves implementation of the proposed framework for MOGA in the Rhino-Octopus interface and generation of 3D model alternatives at a defined site by using the proposed framework. Octopus is selected because it allows evaluation of multiple objectives as parallel inputs. Octopus utilizes the strength of the pareto evolutionary algorithmic (SPEA 2) structure. It also involves non-dominated sorting methods which allow creating of a pareto optimal solution pool. While adapting the algorithms to Grasshopper components, each objective's weight is defined in a range to effect the solution pool which is important to get more precise results. The criteria which are represented in the computer environment and used in MOGA are shown in figure 1, Section 2. In this section, architectural design problem and the selected site will be explained, followed by the formal explorations, outcomes and discussion.

4.1. SELECTED SITE AND PROBLEM DEFINITION

In this project, Fikirtepe was chosen as the field of case study (figure 2a). Fikirtepe, as a residential district which is composed of a mostly one-storey housing pattern, is located in Istanbul-Kadikoy in Turkey (figure 2b, 2c, 2d). Fikirtepe was declared as an urban transformation zone by the Law on the Transformation of Areas under Disaster Risk (Law No.6306, 31.05.2012). Because of being in the urban transformation zone, the rapidly changing urban identity, and given the floor area ratio

constant of 4.00 to encourage the contractors, the design conditions become difficult. Rapidly changing urban identity shortens designing deadlines and the high floor area ratio restricts topological data. Fikirtepe is found suitable to benefit from computational methods in earlier steps of the design process because of these reasons. Using the computational design methods brings not only time optimization and diversity, but also a rich pool of solutions by including multiple parameters simultaneously which are normally heuristically used by designers.

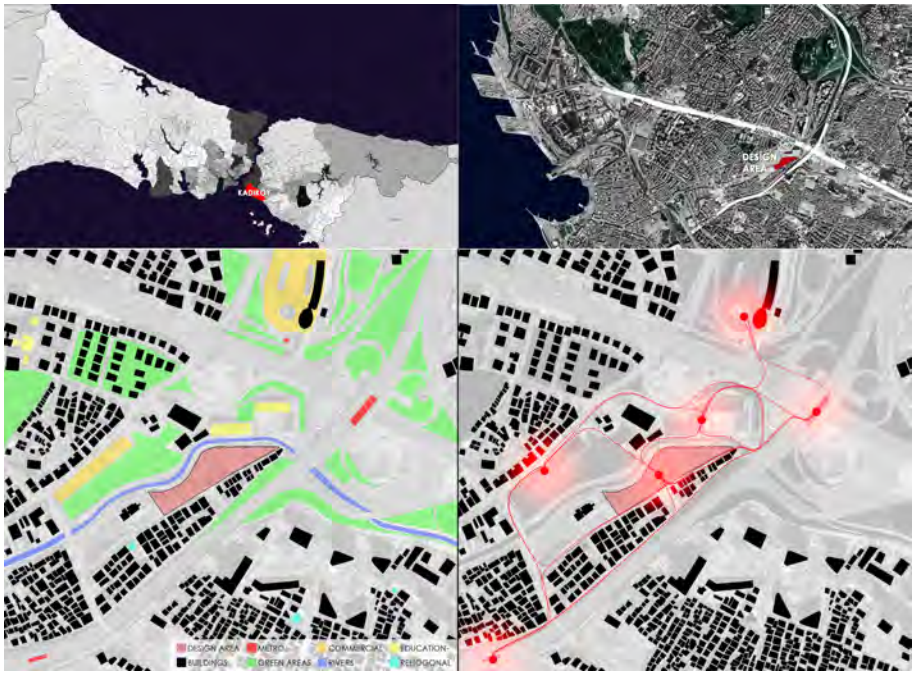


Figure 2. a) Fikirtepe Location in Istanbul, b) Design Site Location In Fikirtepe, c) Design Site and the Neighbourhood Relations, d) Design Site and Pedestrian Connections.

4.2. IMPLICATION OF THE MOGA

In the scope of this study, distances among building blocks, distances from the pavement-street, the balance of area usage regulating the ratio of floor area, and the maximum height were selected as zoning regulation parameters. An additional goal, controlling the effectiveness of site usage in master plan scale, was defined by the authors. As an environmental control module, an existing solar analysis tool was integrated with the algorithm. Another module that was used in the case study is an agent-based pedestrian movement simulation. The connections between the selected area and the existing street nodes were used as a foundation for constitution of the pedestrian movement simulation. In terms of the domain-specific design goals, housing units-residential usage were selected and defined in a matrix-based layout as nodes. The general information for the algorithm schema is shown

in figure 1. In addition to this, the specific objectives and sub-objectives which were used in the case study are explained below. Among different objectives, the pedestrian simulation was executed only once, in the beginning of the evaluation process, because of its heavy load on the system. The objectives area was checked in a tolerance range to preserve beneficial results.These criteria were formulated using the notations below (figure 3).

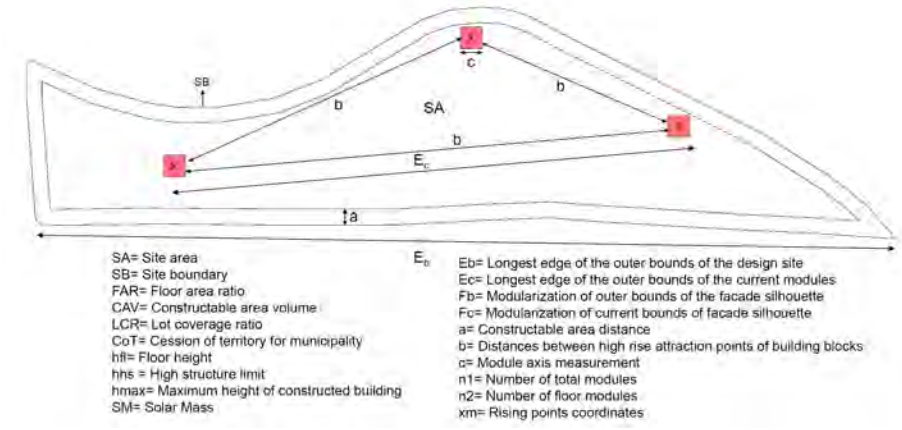


Figure 3. Notations of the Site.

4.2.1. Regulations

In this phase, the regulation criteria were defined for the further steps of the design and selection process (figure 4a). A boundary shape was generated to define a volumetric constraint for representing the constructible area (figure 4b). This sub-module checked whether the generated floor area was in the tolerated number interval. The number interval was calculated based on the given calculations. The total constructable area was checked by an additional tolerance constant for not neglecting the potential results

4.2.2. Physical Environmental Parameters

The solar performance of the solutions was restricted by a dynamic solar calculation system based on the location information of the site (figure 5).

Maximizing the solar efficiency $\left(-\sum_{SM} \rightarrow MIN\right)$

4.2.3. Domain Specific Design Goals

A gridal axis system was generated to represent the modules of housing. The grid nodes were multiplied in the Z direction to represent a 3dimesional axis system. To represent the rising attraction points, a dynamic gene-pool was constructed (figure 6).

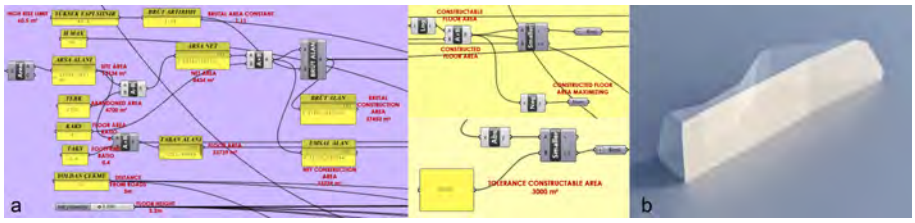


Figure 4. a) regulation criteria and control, b) boundary volume.

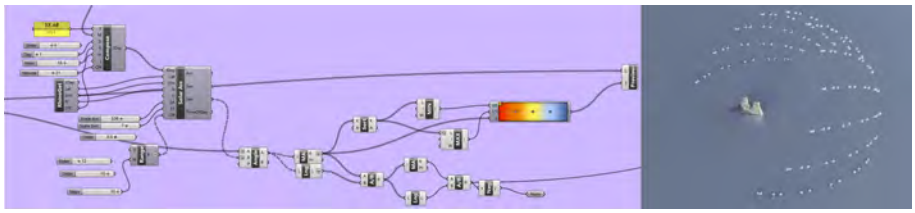


Figure 5. Checking the solar efficiency ratio.

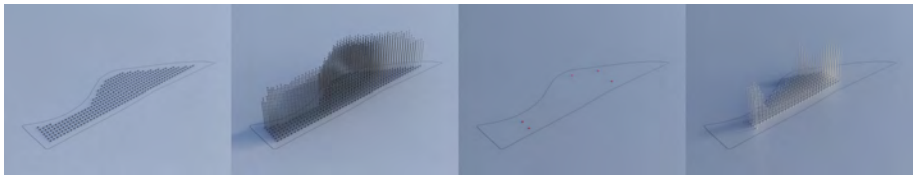


Figure 6. Domain Specific Design Goals.

4.2.4. Designer Specified Goals

A facade density system was developed to define the percentage of solid-void areas of the solutions which is formulated as Fb/Fc<0.8 and (Fb/Fc)→MIN

The longest edge checking system was generated to prevent inefficient usage of the site which is formulated as Eb/Ec<1.7 and (Eb/Ec)→MIN

4.2.5. Urban- Global Analysis

The locational and topographical information was derived from the Rhino interface. Pedestrian analysis was generated using the environmental parameters. The circulation area was maximized by solutions. Site constraints were applied (by laws) to the boundary to generate a constructible volume (figure 7).

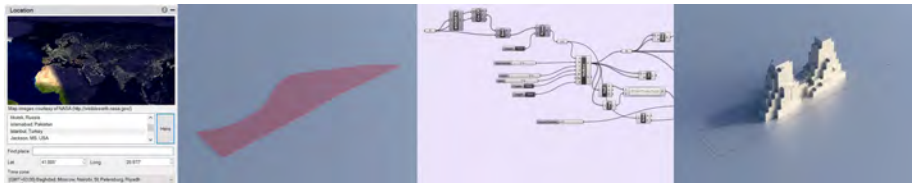


Figure 7. Urban/Global Analysis and executing the algorithm.

4.3. FINDING AND OUTCOMES

The results are gathered above (figure 8), sorted according to generations. Some pareto optimal non-dominated solutions are represented as final results of each generation. The case study was carried out simultaneously with an architectural design office. The design office used conventional systems as designing tools. Comparing the proposals of the design office (figure 9) to those of the case study, there were some topological similarities found in the final results. It may be stated that the similarity was due to the dominance of the regulations of the site. On the other hand, the time consumed in the case study was much shorter than the conventional methods in the design process.

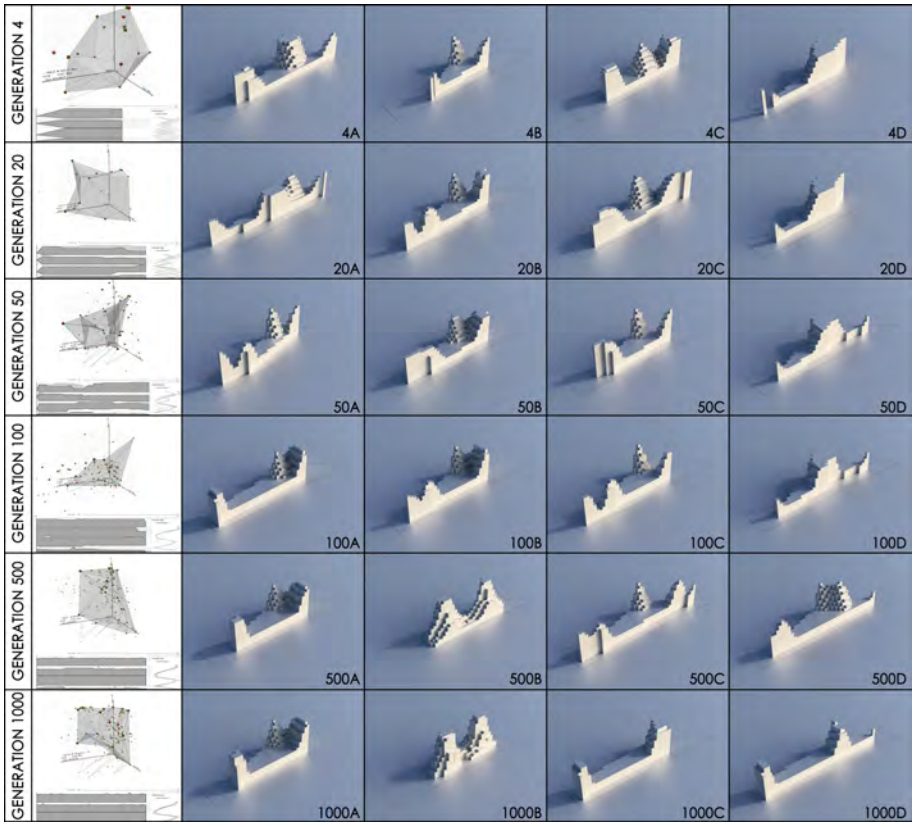


Figure 8. Final outputs of generations.



Figure 9. The architectural office proposal.

Additionally, the well-defined parameters increased the quality of the case study based on defined criteria compared to conventional methods in terms of final results. Moreover, the diversity language of the results in the conventional methods were much higher than that of the predefined algorithm which was used in the case study. Reaching the richness of language diversity to adapt the algorithm probably takes more time than conventional design processes. So, using the algorithm in unique design processes seemed to be inefficient in the context of this study.

5. Conclusion

The study shows that the process of defining the fitness function in the multi optimization design problems plays a crucial role in generating useful 3D mass alternatives. We argue that multi-objective genetic algorithmic dynamic modules have potential to respond to the required flexibility in design process. User interfaces giving opportunity to add new customized modules are crucial in the case of multi-objective genetic algorithms (MOGA), apart from the simultaneous connection of different design objectives. By adding, subtracting or manipulating the objective criteria, the proposed framework might be adapted to different design contexts. In different design domains, the fitness functions of the objective modules can be defined based on the requirements. Both the usage of non-dominated multi objective genetic algorithms and also usage of a dynamic/adaptable modular framework might be helpful in the earlier steps of the design process specially in design offices that accumulate expertise and experience in similar design domains. The alternatives achieved from the execution of MOGA in the case study might be criticised from the point of formal similarities. This is because the dependency of the initial assumptions, such as regulation objectives. In the selected site, the usage of maximum floor area and constructible volume are tightly defined, however in another study the results would be different. When the architect is expected to generate design alternatives in a limited time for a given site, the proposed framework has potential to search for 3D formal possibilities and to give rapid feedback to designers.

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EVOLUTIONARY URBANISM

Exploring Form-based Codes Using Neuroevolution Algorithms

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Abstract. Form-Based Codes are legal regulations adopted by local government that allow specific urban forms to be achieved. Such codes have a significant impact on the performative potential of the urban environment. This paper explores the possibility of using a neuroevolution algorithm to elucidate the complex relationship between Form-based Codes and their performative potential. More specifically, Compositional Pattern Producing Networks (CPPN) are used to generate parameter fields, which then drive the generation of varied urban models. For evolving the CPPN networks, a neuroevolution algorithm is used, called Neuroevolution of Augmenting Topologies (NEAT). In order to test the feasibility of the proposed approach, an abstract experiment is described in which a population of urban models are evolved, optimising a set of performance criteria related to the vista and location of the residential units.

Keywords. Form-based codes; evolutionary design; neural networks; neuroevolution; urban planning.

1. Introduction

This research explores the use of evolutionary algorithms to help understand the impact that planning codes may have on the performative potential of the urban environment. The research focuses specifically on the development of Form-based Codes (Parolek et al. 2008), which are legal regulations adopted by local government that allow specific urban forms to be achieved. Form-based Codes differ from the more common Use-based Codes, which focus on the division of areas of land into zones within which various uses are permitted. They also differ from various other type of planning and design guidelines, which tend to be advisory rather than regulatory.

Form-based Codes have a significant impact on the performative potential of the urban environment. To date, Form-based Codes have been applied in relatively

low density types of scenarios. In high density mixed-use districts, the interactions and possible conflicts between urban blocks are accentuated. As such, it is argued that Form-based Codes could be used to control and regulate these interactions and conflicts. However, the relationship between the urban forms and their performative potential is highly complex and cannot be easily understood by the planners developing such codes. This research therefore explores the idea of using evolutionary algorithms to help elucidate this relationship.

Evolutionary algorithms are loosely based on the neo-Darwinian model of evolution through natural selection. A population of individuals is maintained and an iterative process applies a number of evolutionary procedures that create, transform, and delete individuals in the population. In order to evolve urban models, two types of procedures need to be defined: a developmental procedure that generates different variants of urban models and one or more evaluative procedures for evaluating the performative potential of each urban model. These procedures need to be defined by the planner in order to incorporate variables and objectives that are seen as being relevant and worthy of investigation.

In general, the developmental procedure starts with a set of parameters encoded as genes in the genotype, and then generates urban blocks for all the parcels in the site area. The aim is to generate urban blocks that can be used as a basis for developing Form-based Codes. However, such codes should still allow significant flexibility, so that architects can develop designs that are diverse and that vary in their specific configurations and layouts. As a result, the urban blocks that are generated must remain relatively abstract, consisting mainly of a massing model.

One of the key challenges when creating such a developmental procedure is encoding variability over the site area. For example, depending on the local context, it may be preferable that the urban blocks at one side of the site have a different typology or different height from the urban blocks at the other side. The question is, how can this variability be efficiently encoded in the genotype? A number of researchers have used parametric modelling techniques to generate or model Form-based Codes. For example, see Kim et al. (2011), Janssen at al. (2016), and Schnabel and Ayadin (2017). However, in these previous examples, the parametric modelling process was not part of an evolutionary system and as a result many aspects were still manually controlled. Since this research aims to evolve urban models, a fully automated model generation process is required.

One approach is to define a genotype that directly encodes all the parameters for all the parcels on the site. However, this would result in a very large number of genes with a high-dimensional search space that would frustrate the evolutionary process. Furthermore, since all the genes would be totally independent from one another, it would also likely result it urban models incorporating many sudden changes from one parcel to the next.

In this paper, an alternative approach is proposed using a neuroevolution algorithm to generate and evolve urban models. Section 2 gives a brief overview of the proposed approach and section 3 presents a demonstration. Finally, section 4 draws conclusions and discusses future research directions.

2. Proposed Approach

The proposed approach uses a type of neural network called a Compositional Pattern Producing Network (CPPN) for generating variability over the site and a neuroevolution algorithm called Neuroevolution of Augmenting Topologies (NEAT) for evolving CPPNs. Together, this pair of algorithms is known as CPPN-NEAT. For more details, see Stanley and Miikkulainen (2002) and Stanley (2007).

2.1. GENERATING VARIABILITY

The developmental procedure needs to generate varied urban blocks for the parcels on the site. To achieve this, the CPPN is used for generating a series of patterns that cover the entire site area, referred to as parameter fields. These parameter fields allow parameter values to be assigned to each parcel in a way that is highly generic and also very compact.

The CPPN neural network has two input nodes, zero or more hidden nodes, and one or more output nodes. The inputs and outputs are all normalized, in the range [0.0, 1.0]. The two CPPN inputs are the position on the site, defined as (u,v) coordinates on a normalised two-dimensional parametric surface that covers the whole site area. The CPPN outputs are the normalised parameter values for a specific (u,v) position in the parameter field.

Each parcel on the site is assigned a set of parameter values through a three step process of sampling the parameter fields. First, the (x,y) coordinates for each parcel centre point are normalised by converted them to (u,v) coordinates. Second, the (u,v) coordinates are fed into the CPPN, thereby generating a set of normalised parameter values. Third, the normalised parameter values are mapped to non-normalised values that can be applied within the user-define parametric models. These parametric models are then used to generate the parcel blocks,

An urban model will consist of many parcel blocks. The generation of the urban model needs to ensure that certain global constrains are met. Three constraints are considered: required area constraints, plot ratio constraints, and block typology constraints. First, the required area constraints define the required floor areas for different programmatic functions. Second, the plot ratio constraints define the maximum and minimum plot ratios for the different programmatic functions. These are necessary in order to avoid evolving urban models with unrealistically high or low plot ratios. Third, the block typology constraints define a selection of user-define parametric typologies that can be used for generating blocks. These typologies should ensure that the spaces that are generated are appropriate for the programmes in question. This includes accessibility to the circulation system and accessibility to daylight and fresh air.

2.2. EVOLVING URBAN MODELS

The NEAT evolutionary algorithm evolves these CPPNs by encoding the neural network in the genotype, including all the hidden nodes, the weights, and network typology. Such neuroevolution algorithms need to overcome certain key challenges relating to the diversity of networks in the population. The NEAT algorithm uses three key techniques: tracking genes with history markers to allow

crossover between networks with different topologies, applying speciation to preserve innovations, and developing topologies incrementally from simple initial structures. On benchmark problems, the NEAT algorithm performs better than many other contemporary neuro-evolutionary techniques. For more details on the CPPN-NEAT approach, see Stanley and Miikkulainen (2002).

In order to test the feasibility of the proposed approach, an experiment is described in which a series of urban models are evolved.

3. Demonstration

The demonstration scenario considers a theoretical urban site, 1km x 1km square, situated on the waterfront facing a promenade (figure 2). On either side, a set of existing high density urban areas are assumed to exist, overshadowing some of the site. At the back, the site faces onto a noisy expressway.

For this site, a fixed street pattern is assumed, consisting of an orthogonal grid of primary and secondary streets. The primary streets (26m wide, including pavements) divide the 1km square are into a 3 x 3 grid, and the secondary streets (14m wide, including pavements) further subdivide each grid a smaller 3 x 3 grid. This results in a 9 x 9 grid, with 81 relatively small urban parcels measuring 96m x 96m.

The task for the planner is to create a set of Form-based Codes for a mixed-use urban district that would cater for 100,000 people, including both residential and commercial facilities. The research aim is to evolve urban models for the site that would maximise desirable qualities and minimise undesirable qualities.

3.1. DEVELOPMENTAL PROCEDURE

The developmental procedure consists of three main stages of generation: normalised parcel parameters, mapped parcel parameters, and parcel blocks.

3.1.1. Stage 1: Generation of normalised parcel parameters

For this demonstration, a CPPN is set up to create four parameter fields. The first field is used to define the location of three open parks within the site. The second and third fields are used to define the residential and commercial plot ratios. The fourth field is used to define a rotation of the block on the site.

Normalised parameter values are generated for each parcel on the site by sampling the parameter fields.

3.1.2. Stage 2: Generation of mapped parcel parameters

For each parcel, the normalised parcel parameters are mapped to values that directly relate to the blocks generated in the next stage. The first and fourth parameters have very simple mappings. The first is used to define a rotation parameter for the block massing on the site. The normalised parameters in the range [0.0, 1.0] are proportionally mapped to {0, 90, 180, 270}. The fourth parameter is used to define the park parameter, which can have one of two values: {0, 1}, with 1 indicating that it is a park. The parameter values for all parcels are sorted, and the

parcels with the lowest parameter values are assigned a value of 1.

The second and third parameters have more complex mappings. These are used to define the the residential and commercial plot ratios. The complexity is due to the global constraints that need to be taken into account, namely the total floor area needs to be correct, and the plot ratios need to be within the allowable range.

For this demonstration, the residential area is set to 2.4 million m2 and the commercial area is set to 1 million m2. The minimum and maximum plot ratios for both residential and commercial programmes are set to 0.4 to 6.0. This results in a total plot ratio in the range [0.8, 12.0].

Given a set of n parcels, the plot ratio, PR , of each parcel is:

$$PR = \frac{\left((A - (\sum_{i=1}^{n} a_i \cdot PR_{\text{min}})) \cdot \left(p / \left(\sum_{j=1}^{n} p_j\right)\right)\right) + (a \cdot PR_{\text{min}})}{a} \quad (1)$$

where A is the required total floor area for all parcels, PR_{min} is the minimum allowable plot ratio, a is the area of the parcel, and p is the parameter value for the parcel. The same formula is used to calculate both residential and commercial plot ratios.

This calculation is performed for all parcels, and if the resulting plot ratio of any of the parcels is greater than the maximum allowable plot ratio, then all parameter values are incremented by a small amount, and the resulting plot ratios are recalculated. This process is repeated until no parcels exceed the maximum allowable plot ratio. (Incrementing all parameter values by a small amount results in a redistribution of plot ratios, so that those with low values increase a little and those with high values decrease a little.)

At the end of this stage, each parcel will have four mapped parameters: the park toggle, the residential plot ratio, the commercial plot ratio, and the block rotation.

3.1.3. Stage 3: Generation of parcel blocks

For each urban parcel, the mapped parcel parameters are used to generate a block. Three typologies are defined, labelled as A, B, or C. Type A is a perimeter block typology, with perimeter units (maximum three stories high) arranged around a courtyard, with the possibility of an additional tower block in the centre. Type B is a slab block typology, with four slabs blocks arranged around a courtyard. Type C is a podium block typology, with variable sized podiums and either one or two towers. For typologies A and B, the lowers floors are assigned as commercial and upper floors as residential. For Type C, the podium is commercial and the towers above are residential.

The typologies are selected based on the sum of the two plot ratios, as follows:

- Type A: for parcels where the plot ratio sum is in the range [0.8, 3.5]
- Type B: for parcels where the plot ratio sum is in the range [3.5, 6.0]
- Type C: for parcels where the plot ratio sum is in the range [6.0, 12.0]

Once the typology has been selected, a block is then generated using a parametric modelling procedure. The number of floors in the model are calculated in order to

achieve the required plot ratios for both residential and commercial programmes. The process of generating these blocks is not described in detail as it is relatively straight forward using typical parametric modelling tools.

3.2. EVALUATIVE PROCEDURE

The developmental procedure creates variants of urban models that all abide by the specified constraints, including overall minimum and maximum plot ratios and a fixed total floor area for residential and commercial programmes. However, each model will also differ with respect to various other performance criteria. In order to be able to evolve urban models, an evaluative procedure is required for calculating a relative fitness measure.

For this demonstration, the evaluative procedure focuses on the residential units. (Although the commercial floors are not directly evaluated, they may still have an impact on the quality of the residential units.) Each urban model has approximately 18 thousand units, each between 108 to 324 m2. (Note that when detail plans are developed, these larger unit may be subdivided into smaller apartments.)

For the evolutionary process, the evaluative procedure must assign a single overall score to the whole urban model. The strategy taken is to first calculate a 'quality' score for each residential unit and to then calculate the fitness of the overall urban model as the average score for the worst 25% of the units. This fitness score ensures that the evolutionary pressure is always focusing on reducing the number of badly performing units.

The quality score for each unit includes two aspects: the quality of the vista and the quality of the location. For each of these two aspects, a score is assigned in the range [-1.0, 1.0], indicating a range from bad to good, with a zero score indicating an acceptable quality. The score for a particular unit is taken to be the minimum (i.e. the worst) of these two scores.

3.2.1. Evaluation procedure for vista quality

The vista procedure aims to quantify the potential quality of the vista of a residential unit. Depending on the block configuration, a unit can have between one and three exterior facades, facing in different directions. (For example, a corner unit would have two facades.) For each unit, the overall vista quality is calculated as the maximum vista score of all the facades. The reasoning behind this is that it is assume that when individual units are designed in detail, then designer will select the best vista as the primary direction for the main view and windows.

For each facade, the procedure calculates scores for three performance objectives, all in the range [-1.0, 1.0]. The overall vista score for the facade is defined as the minimum of these three performance scores.

- Unobstructed view: The horizontal unobstructed view calculated from the centre of the facade polygon for a 60 deg cone of vision, with a maximum depth of 100m. A score of -1.0 indicates that the area of the cone of vision is 0, while a score of +1.0 indicates that area of the cone of vision is equal to the maximum area.

- Scenic view: The visibility of a set of desirable and undesirable points calculated from the centre of the facade polygon. 12 undesirable points are placed along the expressway and 12 desirable points are placed along the seafront promenade. A score of -1.0 indicates that all undesirable points are visible, while a score of +1.0 indicates that all desirable points are visible.
- Insolated view: The visibility of the sun during the two solstice days (21st June and 21st December) calculated from the centre of the facade polygon. For each solstice day, 7 points are defined, starting and ending with sunrise and sunset. A score of -1.0 indicates that the sun is always visible, while a score of +1.0 indicates that the sun is never visible. (Note that this demonstration is assumed to be located in the tropics, where the sun is never desirable.)

Typically, each urban model will have approximately 26 thousand individual residential facades. Since each evolutionary run may result in approximately 30 thousand urban models being generated, this results in approximately 780 million facades being evaluated. It is therefore essential that the procedure is fast to execute. The scores for the performance objectives are all calculated based purely on the geometry of the model, using a raycasting algorithm.

3.2.2. Evaluation procedure for location quality

The location procedure aims to quantify the potential quality of the location of a residential unit. For this procedure, the proximity to desirable and undesirable locations are calculated. Desirable locations are given a score in [0.0, 1.0] while undesirable locations are given a score [-1.0, 0.0]. For each unit, the overall location quality is calculated as the sum of the maximum desirable score and the minimum undesirable score. This results in an overall location quality score in the range [-1.0, 1.0].

Two desirable locations and one undesirable location are defined, as follows:

- Proximity to parks: The minimum straight-line distance from the unit to one of the three parks is calculated. A score of 0.0 indicates that the unit is more than 300 meters from the parks, while a score of 1.0 indicates that the unit is right next to a park.
- Proximity to train station: The minimum straight-line distance from the unit to the train station (located adjacent to the expressway) is calculated. A score of 0.0 indicates that the unit is more than 500 meters from the station, while a score of 1.0 indicates that the unit is right next to the station.
- Proximity to main roads: The minimum straight-line distance from the unit to any of the main roads is calculated. A score of -1.0 indicates that the unit is right next to a main road, while a score of 0.0 indicates that the unit is more than 30 meters from the main roads.

3.3. RESULTS

The CPPN-NEAT algorithm was used to evolve a population of 200 individuals for 300 generations, using the NEAT Python library (NEAT-Python 2016). For a description of the various configuration settings, see NEAT-Python Docs (2016). For the initial population, a set of fully connected neural networks was randomly

generated with two input nodes (for the u and v values), 5 hidden nodes, and 4 output nodes (for generating the 4 parameter fields). The minimum and maximum weights were set to -30 and 30 respectively, with a weight standard deviation of 1. The activation function was set to only use the sigmoid function. For reproduction, elitism was set to 10 and the survival threshold was set to 0.2. For speciation, the compatibility threshold was set to 2.3 and the maximum stagnation threshold was set to 10. For all other settings, default setting were used. In total, approximately 27 thousands different urban models were evolved, taking approximately 15 hours on a laptop with an Intel i7 2.3GHz processor with 4 cores.

The improvement in fitness over time is shown in figure 1, ending at a value of -0.03. Thus, in the final evolved urban model, the average overall quality score of the worst 25% of residential units was -0.03. This is just below the acceptable level (which is defined as being 0).

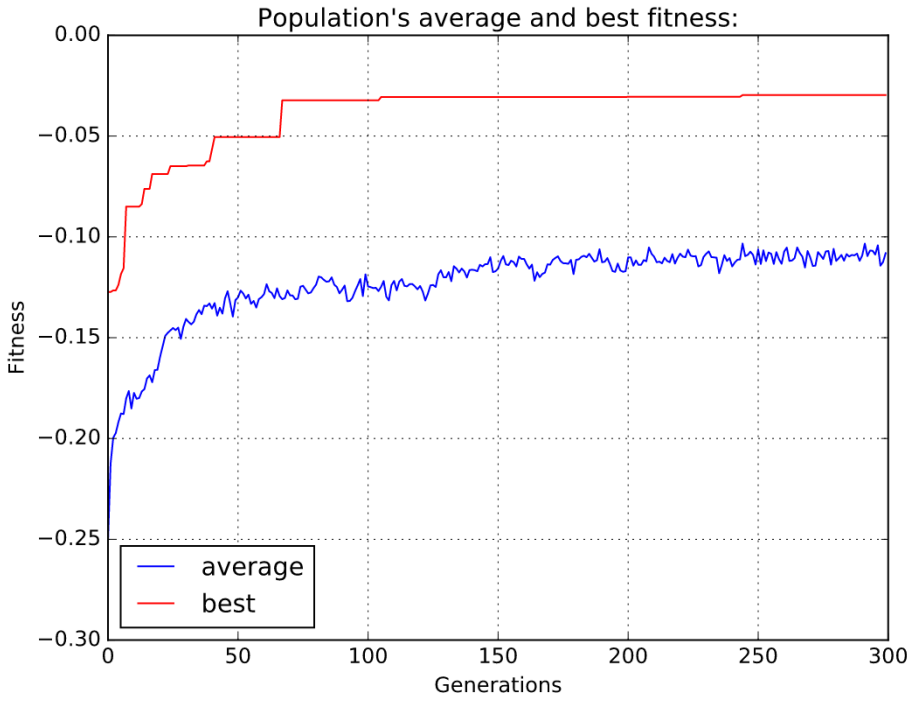


Figure 1. Fitness during the evolutionary run, showing best and average fitness in the population.

The urban model with the highest score is shown in figure 2. The residential programme is shown in yellow, the commercial in blue, and cores in dark grey. An analysis of the different species revealed certain key common traits. First, the evolved urban models all have the parks close to the waterfront and have two clearly defined zones - a mainly residential zone on the left side facing the water-front and a mainly commercial zone on the right side facing the expressway. In

addition, the type B blocks have been mostly eliminated due to the fact that those typologies tend to have residential units with low vista scores. Only when there are sandwiched between A and C typologies do the B typologies perform well.

The plot ratios for residential and commercial programmes have also been adjusted so as to minimise the number of residential units close to the main roads. By pushing up the residential plot ratio in the commercial zone, the type A perimeter block typologies have become almost completely commercial, with only a few residential units remaining in the residential tower

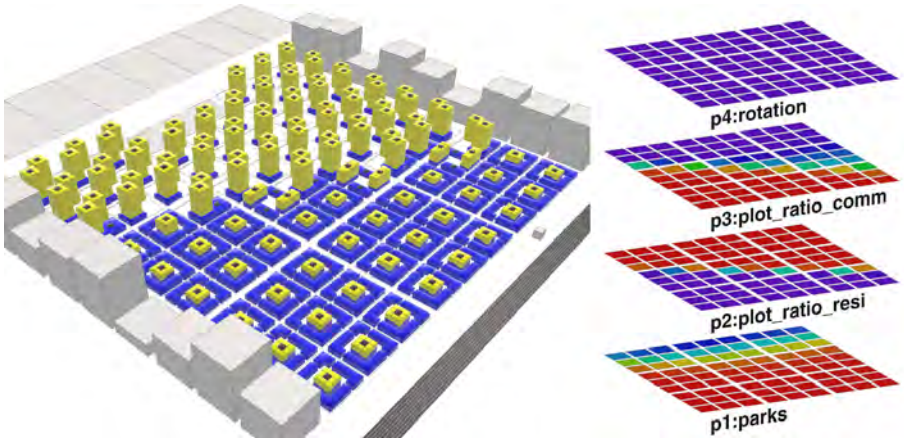


Figure 2. The best performing urban model in the population (ID= 26900). Left: the 3D model. Right: the four parameter files used to generate the model.

4. Conclusions

This paper explores the possibility of using CPPN-NEAT algorithm to elucidate the complex relationship between Form-based Codes and their preformative potential. The demonstration has shown how CPPNs can be used for generating variability in large scale urban models while still abiding by certain constraints. Furthermore, the paper has also explored how the performative potential of these urban models can then be evaluated using simplified metrics that are fast to execute.

In future research, the developmental and evaluative procedures can be further elaborated in various ways. For the developmental procedure, the site as currently defined is highly simplified. More realistic scenarios could include the evolution of variable street networks with different patterns, the evolution of urban fabrics that include both empty and occupied parcels, or the evolution of urban transformations that unfold over time. For the evaluative procedure, many other aspects could be analysed beyond vista and location quality. This may also lead to multi-objective approaches being considered.

Initial experiments in evolving designs using the NEAT algorithm are showing some promising results. However, the species in the current population are quite

similar, with the overall diversity of urban models being poor. It is believed that higher performing urban models could be evolved by either adjusting configuration settings and/or by creating bigger populations. In general, further experiments need to be conducted in order to investigate the impact that various CPPN-NEAT configuration settings have on the effectiveness of the evolutionary search process.

In order to be able to conduct such additional experiments, one of the key challenges is execution speed. The execution time is currently already more than half a day, and with larger populations, this can easily increase to a number of days. In the experiments conducted so far, the developmental and evaluative procedures are being executed in parallel, on multiple cores within a single machine. In order to achieve further significant increases in execution speed, it is possible to also distribute the execution of these procedures over multiple machines. In the next stage of the research, a distributed implementation of the CPPN-NEAT algorithm will be developed, thereby allowing a large number of additional experiments to be conducted.

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SPECULATIVE URBAN TYPES

A Cellular Automata Evolutionary Approach

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Abstract. The accelerated rate of urbanization in China is the motivator behind this paper. As a response to the observed monotonous housing developments in Suzhou Industrial Park (SIP) and elsewhere our method exploits Cellular Automata (CA) combined with fitness evaluation algorithms to explore speculatively the potential of building regulations for increased density and diversity through an automated design algorithm. The well-known Game of Life CA is extended from its original 2-dimensional functionality into the realm of three dimensions and enriched with the possibility of resizing the involved cells according to their function. Moreover our method integrates the "social condenser" as a means of diversifying functional distribution within the Cellular Automata as well as solar radiation as requested by the existing building regulation. The method achieves a densification of the development from 31% to 39% ratio of footprint to occupied volume whilst obeying the solar radiation rule and offering a more diverse functional occupation. This proof of concept demonstrates a solid approach to the automated design of housing developments at an urban scale with a ,yet limited, evaluation procedure including solar radiation which can be extended to other performance criteria in future work.

Keywords. Integrated Speculation; Generative Urbanism; Cellular Automata.

1. Introduction

Accelerating urban development has been - and still is- one of the key strategic plans of China in increasing its economic development. This strategy has worked

well as an economic development tool but has also created a real estate market full of monotonous, vertical, repeated- tower arrangements for housing. These towers are essentially two dimensional in the sense that typical floor plans are simply extruded almost arbitrarily regardless of any context except the sunlight direction and conforming to existing building regulation. The exploitation of the third dimension that would increase density is very low. Our main case study under examination is the city of Suzhou in the Yanze river delta and its new Industrial Park (SIP), newly constructed in the last 25 years.

In Suzhou Industrial Park, the acceleration of construction of housing for urban population has eroded the agricultural land use in the area of Suzhou to about 1.5% of the total while the need for urban growth has not subsided. Apparently, there is a discrepancy between the still increasing demand for housing supply and the very limited availability of land for new developments. A solution to this discrepancy could be the densification of existing housing developments. A higher density achieved through densification above ground - in the third dimension - would sustain the existing greenery within the developments whilst providing more living space. A densification whilst obeying existing building regulations would result in a more efficient land use while sustaining an equally high standard of living. We examined one example of a monotonous tower housing development, analysing the determining building parameters including building regulations and their impact on the actual planning decisions made by the local planning office which led to the repeated tower pattern. The project then employed architectural computational techniques to investigate through qualitative and quantitative methods how to increase housing density. We transformed a standard cellular automata mechanism into an integrated generative and evaluative parametric system with evolutionary principles. In this paper we examine the possibility for optimisation of the building density, expressed as a ratio between volume and footprint, along with the optimisation of the sun exposure of the surfaces of the building, expressed as solar incidence number, as per regulations.

A novel introduction in our system, is the parametric representation of the social condenser, a constructivist concept of overlapping and intersection of programs within a building, employed by in the 20th century by architects such as Rem Koolhaas & OMA, Ivan Leonidov, Mosei Ginzburg. We were able to produce results with increased density and similar parametric profile of the current residencies, thus in theory similar quality of life. Apart from the integrative nature another innovative part of the system is the inclusion of programmatic variety in three dimensions, thus breaking the functional monotony we encounter in Chinese megacities and walled communities. The project is expected to provide an understanding of how housing density contributes to the sustainable development of the built environment of new towns like Suzhou Industrial Park, by stopping the transformation of land from agricultural and rural to urban (figure 1).



Figure 1. Suzhou Industrial Park with location of one case study noted.

2. Background

The project began with an examination of the volumes that repeated housing towers create in the Chinese urban landscape. By looking at the case study of Butterfly Bay though we discovered that the repetition of 10 cellular types of apartments defined the limited diversity of the towers. These cellular types, drove us to use cellular automata as the main engine in our generative system. Unclear termination rules in the cellular automata paradigm, i.e automata can run indefinitely, drove us to use evolutionary methods as optimization techniques.

2.1. CELLULAR AUTOMATA

Cellular automata are not new in the areas of designing dense towers or dense housing environments. Herr (2007) has in the past explored the mechanism of cellular automata as a tool for architectural designing and adapting an existing strategy of tower design with increased density. In a following work Herr (2015) has also explored the adaptation and exploitation of Cellular Automata in architectural design computation processes, ranging from the deterministic for generating a plan to the playful, conversational-with-the-designer use of cellular automata. Others (Khalili et al. 2015) equally recently have used Cellular automata as an engine for growth in dense housing conditions in the Netherlands, similarly with the present paper, focusing on accessibility, density and light exposure, however at a significantly smaller scale than the present China study.

The rule based creation of morphologies by the Cellular Automata is not able to discriminate produced solution per performance criteria such as solar radiation. Only the introduction of an evaluation algorithm connected with a search procedure would make it possible to discriminate better solution versus worse ones. The present method feeds the quality values of the evaluation algorithm into a Simulated Annealing or an evolutionary procedure to optimize the solution production.

2.2. SIMULATED ANNEALING

The "Simulated Annealing" is a robust search algorithm which unfortunately doesn't guarantee to lead to the global maximum of the solution landscape, but it is efficient and successful in discontinuous and fractal solution spaces since the algorithm can overcome local maxima peaks and minima valleys in the landscape.

In the presented case, the fitness of the respective solutions is established through the evaluation of solar radiation and density as the ratio of volume to footprint using different simulation and geometric evaluation tools to establish a single value of quality q which can be fed into the "Simulated Annealing" algorithm to enable an efficient search for good solutions.

The morphologic representation of the solution is the result of the applied Cellular Automaton which itself includes elements of randomness inbuilt into the growth algorithm but based on predefined starting conditions. The starting conditions which are to some extent the predetermining factors for the morphology of the solution are mapped towards the quality values of the fitness function. Depending on the results of the fitness function the initial conditions of the growth algorithm are adapted and the next (i+1) iteration of the morphological representation is grown and will undergo a fitness examination.

2.3. EVOLUTIONARY METHODS

. The creation of individuals by the cellular automaton is based on few parameters such as the grid size, the height and number of floors and specifications of the "Game of Life" itself. These parameters contained in the genome of the created individual are mapped against a quality value which represents the individual's performance per the set solar radiation and density requirement. The afore described search algorithm selects the best 50% of the created individuals and creates a new population through a randomized cross over recombination of selected individuals together with the selected individuals itself. The discrimination algorithm simulating a metallurgic annealing process, will only slowly focus the search radii as the 'temperature' decreases sustaining different areas of search within the solution landscape. Thus, the convergence of the evolutionary process can be controlled through the speed of 'temperature' decrease.

The combination of the search algorithm and the evolutionary process are implemented in Rhino Grasshopper TM and respective plugins thereof. The current implementation allows for population sizes of around 100 individuals to keep the system with an acceptable and reasonable response time using standard personal computation power.

3. Method

The project examined one housing case study in Suzhou Industrial Park (figure 2) and employed computational design methods to speculate about possible outcomes on increased density in SIP. The methods employed in the research were qualitative and quantitative in nature.

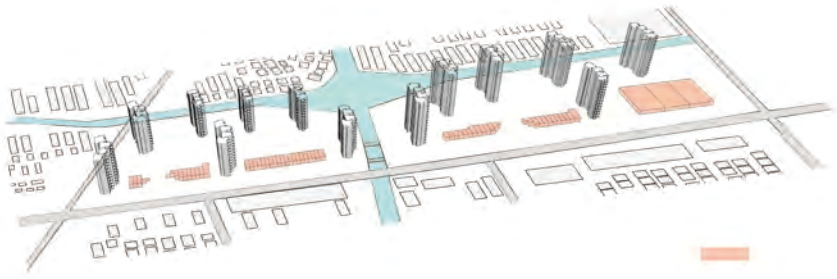


Figure 2. HuDieWan digital model, the case study examined.

3.1. FRAMING THE PROJECT'S BENCHMARK

3.1.1. Quantitative methods

The quantitative methods were focused in the speculative design experiment using computational design methods. Initial benchmarks were established by the Suzhou Industrial Park case study Butterfly Bay to other known case studies in Asia, known for their effectiveness and high density-

3.1.2. Setting Parameters and criteria for the cellular automata.

To be able to establish the parameters and constraints for the basic cellular automata to be used as a generative system we referred to the 'Technical specification for planning and design of residential area in Suzhou Industrial Park'

The regulation establishes basic metrics, maxima and minima in specific parts and functions of the building and at the same time establishes potential evaluation metrics of the performance of the building. We translated these parameters into a table that describes them along with the manner in which they are represented in our system and the evaluation/constraints criteria (table 1). The regulation establishes other criteria as well, such as fire truck and ambulance access, parking sizes and numbers, but we did not incorporate these in our current version of the algorithm.

3.2. IMPLEMENTATION: RHINO- GRASSHOPPER

The computational modeling environment was Rhinoceros with Grasshopper handling the parametric and evolutionary roles. We used the Rabbit cellular automata plugin, with our own extension in the three dimensions. The evolutionary algorithms used was the Galapagos evolutionary solver contained in Grasshopper. For the lighting simulation we used the Ladybug grasshopper plugin, connected again with the Rabbit and Galapagos solvers. To measure lighting we did not just restrict ourselves in the initial measurement at the sill of the opening, but established a grid of points on the surface of each cell that would measure incidence of light. This proved cumbersome and computationally expensive making the resulting lighting model difficult to handle and unresponsive.

Table 1. Parameters and evaluation criteria.

Parameters	Sub-Parameters	Geometry in Rhino-Grasshopper	Definition	Evaluation
Building Regulation				
Site	Shape of Site	XY Polyline	Polyline	minimum size
Lighting	hours of exposure per day	any 2d area / usually rectangular	line of sight from Sill to light source(sun)	over three hours per day
Building Height	N/A	Z vector or Z parameter		>1.3 X width of South Facade.
Floor Height	N/A			2.8 -3.5 m
Distance from site boundary	N/A	XY line	Polyline	>15m
Cellular Automata				
Neighborhood Rule	Game of Life	Cellular Automata	Born in a, Survive in u-v	number of housing blocks
	Public Space	Void Space	From Difference of	ratio of housing to public space
Social Condenser				
	Shape of Condenser	Box	XYZ Size; Centre Point; Type	
	Condenser attraction	Sphere	Service radius; Service Strength	distance of each block from condenser

The actual algorithm was on an alternative to Conway's game of life on the cellular automata game known as Conway's game of life and an extension of it in the third dimension. In the original a two-dimensional grid of cells is populated randomly and then rules of density determine whether a cell will be generated, or die and be erased according to how many neighbours it has (figure 3). In this new extension of the game each cell communicates with the other 26 cells around it to determine whether a cell lives or dies. We parameterise the rules in this form: if a cell has K neighbours then a new cell is generated. If the cell has N-M neighbours, then the cell dies because of loneliness or from being overcrowded. For evaluating the Neighbourhood we use the 3d concept of the Moore Neighbourhood (figure 4).

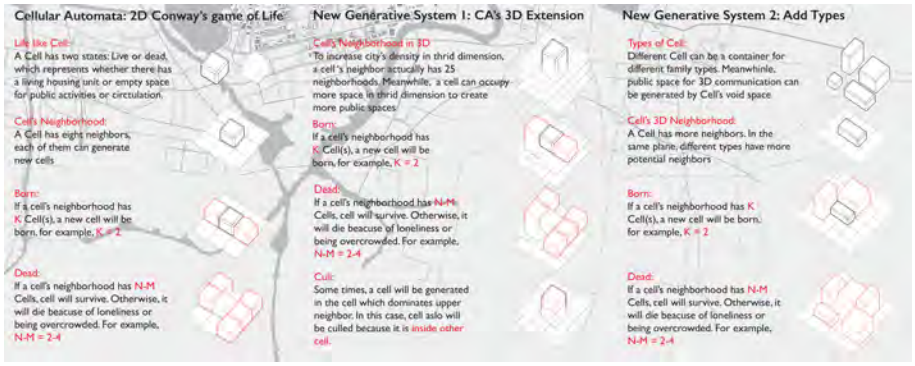


Figure 3. Extension of CA game of life in three dimensions.

In a subsequent improvement of the cellular automata in three dimensions, we also introduce a variety of functions in each cell to diversify the functions in the 3d building. The diversity of the functions inside a housing block work against the monotony of the single-function tower. Public functions are employed as social condensers: a three-dimensional version of neighbourhood centres as they are used in the original planning of the Suzhou Industrial Park. We envisage that the different functions can be represented in the future by different types of cells in the cellular automata mechanism.

However our current proof of concept only uses the maximisation of density and the maximisation of sun exposure as the fitness functions. We are building a proof of concept, evaluating for fitness one parameter at a time. The computational techniques employed in the study were measured in terms of their effectiveness in increasing density while all other parameters and factors remain constant.

Referring back to the building regulations we also established important parameters prioritised by the regulations. In the case of Suzhou industrial park exposure to sunlight of each space for a minimum of three hours per day was crucial on whether the building would receive building permission or not. As such the evaluation mechanism we established would evaluate all models for exposure to the sun, plus increase density in floor area and volume. We were able to increase volume occupancy from 31% to 39%, a small but important increase (figure 5).



Figure 4. Final algorithm of quantitative method, generation and evaluation.

4. Results - Discussion

The results of the First version of the algorithm is presented in figure 5: A maximum height tower, in comparison with towers that resulted from optimal genomes in maximizing density to footprint ratio while still being within the constraints set at the parametric table 1. These results obviously prioritise the footprint rather than a balance in a multi-parametric optimisation.

The results of the third version of the algorithm lead to towers with maximum density to footprint ratio and maximum lighting conditions met, above the 3 hours daily. In this we used the ladybug plugin in grasshopper to simulate and evaluate the lighting conditions. The ladybug plugin evaluates lighting for each different cell, by first creating a grid of points of the surface of each cell, and then calculating the light that reaches those points. Thus the level of lighting as an average for each cell is calculated. The overall lighting for the tower is not computed at all as the regulations prescribe lighting conditions for each room and apartment rather than

each cell. However more diversity in form of the tower was achieved with the inclusion of the social condenser in the grid of the cellular automata depicted in figure 6. A difficulty in this case was the absolute evaluation of the mechanisms involved, since in our implementation a python script was needed for generating the points in the grid for the social condenser. In future work we will incorporate the generation of the condensers in the cellular automata mechanism, a feat that will require multiple types of cells incorporated into the mechanism.

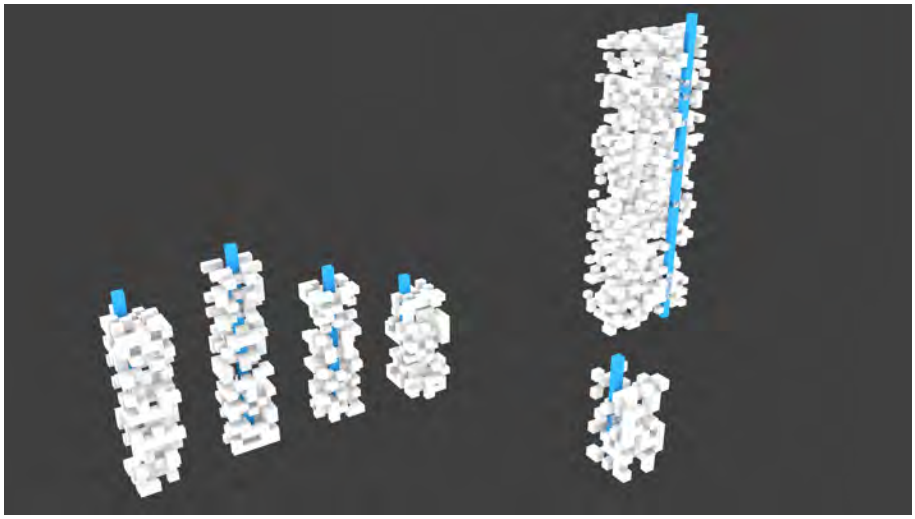


Figure 5. Maximum height tower, along with optimum genomes.

5. Conclusions and Further Work

We have demonstrated that it is possible to design a generative and evolutionary parametric system, integrating programmatic function, floor area, and sunlight exposure along with their evaluating functions. We have shown that it is possible using this automated system to develop large three-dimensional housing blocks, with functional diversity, increasing the density of the housing whilst retaining the size of the footprint. We will continue to developing the system with the inclusion of basic structural and circulation evaluation functions. Further potential of the system lies also in developing a tool that evaluates the building's financial performance, from cost of construction to the price of sale or renting to make a profit in a specific time. Thus we envision that a continuation of this system will lead into an integrated tool, combining the parametric generative system and a multi-parametric evaluation, helping architects and planners deliver competitive designs within fast developing environments. Further papers will follow in developing each of these parameters of the system, along with establishing the social condenser in the algorithms of the cellular automata.

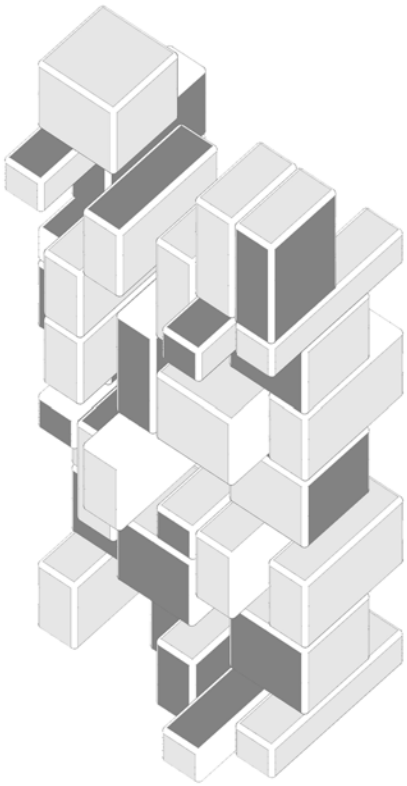


Figure 6. Results of the algorithm with the lighting evaluation according to the building regulation including the impact of the social condenser.

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Spatial Analysis

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INTEGRATION OF SPACE SYNTAX INTO AGENT-BASED PEDESTRIAN SIMULATION IN URBAN OPEN SPACE

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Abstract. MAS can be utilized to analyse macro rules of whole system by simulating a number of active agents. However, simply based on the parameter of specific environment quality and incomplete statistical setting of individual, models of pedestrian traffic in realistic open space have often been imperfect, because the behaviour of people cannot be rationally reflected to the complex characteristic of space. Space Syntax Theory breaks down the space into components and measures each with the straight sight-line of individuals, which can help analyse and quantify pedestrian flow in complicated real-life environment. In this situation, we make an attempt to combine these two in our research, in order to simulate the moving of pedestrian closer to reality. In this paper, Gulou Square, an urban open space close to centre of the city with a large flow of people, is selected as the study site. The results after plenty of simulations and contrast tests can be concluded that with the assistance of Space Syntax Theory, MAS can be more functional solving the problems in sophisticated real-life environment.

Keywords. Multi-agent system; Space Syntax; Open space; Visibility.

1. Introduction

Urban open space facilitates public activities and plays a significant role in urban environment. When designing urban open space, pedestrian simulation is always considered as a potent tool that can be used to lead the initial design of a project. This simulation method is now believed as an integral digital asset to play an increasingly important role in the analysis tool chains.

From the perspective of monitoring pedestrian activities, multiple-agent system has gradually become prevalent among the researchers (Batty & Jiang 1998).

In the very beginning of the study, Center for Advanced Spatial Analysis conducted a significant number of simulations to pedestrians and further explored the reactions and behaviors of pedestrians among a variety of obstacles, which laid a firm foundation for activity simulation of pedestrians in real space (Popov 2007). With the development of pedestrian simulation model, David Schaumann studied computational framework for simulating human spatial behavior in built environment (Schaumann 2016). In addition, Michael Schyndel's crowd modeling in the Sun Life building was able to simulate passenger flow through the design of pedestrian route in large-sized building of multiple-agent system simulation (Schyndel 2016).

However, computer simulation of urban open space is commonly focusing on larger-scaled environment or theoretical analysis. For instances, based on Netlogo platform, the Citybuilder developed by Martin Felsen and Thomas Lechner focused on the simulation of the growth process of cities (Lechner 2004). And the MAGS (Multi-Agent Geo-Simulation) developed by Moulin, which now is used in the study of pedestrian behaviors in the urban environment, was able to facilitate thousands of units possessing the ability of space recognition to interact with each other in 2D and 3D virtual geographical environment (Moulin 2003). It can be inferred, therefore, that how to focus MAS on the specific individuals' route simulation in large-sized environment still lacks of research. The real factors such as height differences, surrounding traffic, visual obstructions, weather conditions and so forth indicate that the simulation model has to contain equal complicated parameters (Johansson 2011). Besides, these factors may also lead to the greater uncertainties. When facing with such situation, MAS's models of pedestrian flow in realistic open space have often been imperfect because there is no appropriate way to rationally reflect the behavior of people to the complex characteristic of open space. Therefore, there should be some other method to cooperate with MAS to conduct more accurate pedestrian simulation.

Based on the measurement of individual straight sight line, Space Syntax Theory can split the space into components, thus helping analyzing and quantifying pedestrian flow (Batty 2004). Previously there has been researches on SST, such as Mohammed Javad Koohsari attempted to depict neighborhood's walking ability based on derivative concepts of Street Integration and Intersection Density, and their further research on impacts of built environment on walking for transport (Koohsari & Sugiyama 2016).

Considering the complementary relation of MAS and Space Syntax Theory, we combine these two in our research, trying to simulate the moving of pedestrian closer to reality. The stimulation attempts to create a feasible method, which allows iterative testing of what-if scenarios to fine-tune the building design against a wide set of requirements related to different building use scenarios, matched to the expectations of different researchers.

2. Methodology

When using program to simulate pedestrians' activities, three key factors are required: space, pedestrian and events (Crooks & Heppenstall 2011). The behavior

of pedestrians is independent, but the occurrence of events is specific reflection of the pedestrians' behavior in the corresponding space (Guido 2007). In this case, multiple-agent system, with its autonomous, heterogeneous and active agents triggering different events in certain spaces based on their properties and behavioral rules, meets the requirements perfectly. Netlogo is a commonly used programing platform hinged on multiple-agent simulation, which comprises three types of agents: turtles, patches and the observer. In Netlogo, two-dimensional world is divided into orthometric grids taken up by patches. Each patch is a piece of ground for turtles to move on. Observers instruct turtles and patches. The simulation process is completed by repetitively executing each procedure, making the basic logical structure a loop. Therefore, these three key factors are embodied as patches, turtles and procedures. Turtles and patches have their respective properties, called attributes, which can be static values, Boolean or even a set of patches. Attributes can be pre-distributed, called parameters, or updated during the procedure, called reporters. The above are basic factors to simulate pedestrians' activities on any spatial area.

2.1. PATCHES

In Netlogo, the space is divided into patches. According to real-life environments, multiply attributes such as unreachable walls, accessible area, starting spots and destinations are given to patches in the form of static parameters (table 1). Meanwhile, the crowd density, which shows the number of turtles on a certain patch, would be updated by reporters.

Table 1. Pre-distributed parameters set for patches..

category	parameters				reporters
name	Wall	Space	Spot	Dest	Density
type	Static Values	Boolean	Static Values	Static Values	Static Values
description	Unreachable walls	Accessible area	Starting spots	Destinations	The number of turtles on a certain patch

2.1.1. Turtles

In the program, after generated randomly in each spot, turtles head for a certain destination. During the process, turtles' activities are determined by a set of attributes. On the one hand, turtles are given different characteristics by pre-distributed parameters (table 2), all of which are set in rational ranges. These parameters can be adjusted as needed to add heterogeneity into turtles. On the other, reporters make it possible for turtles to respond instantly according to the environment. Turtles' reporters include crowdity, dist and accessible. Crowdity reports the total number of turtles on surrounding patches. Dist calculates the distance from the turtle to the closest wall within the scope of sight. Accessible decides if the destination can be seen.

Table 2. Pre-distributed parameters set for turtles.

category	parameters				reporters
name	Speed	Sight	Dest	Tolerance	Crowdity
type	Static Values	Static Values	Patch	Static Values	Static Values
description	Distance turtles move for every step, patch as a unit	Number of patches that can be seen in this direction	The destination of turtles	The maximum number of crowdity that can be tolerated	Reports the total number of turtles on surrounding patches

2.1.2. Procedures

The basic rules of simulation ensure the operation of multiple events.Based on the above settings of space and attributes, the following procedures might be triggered:

Set-human: The program will generate a random number. Only when a certain number was generated would this procedure be triggered, making sure the proper amount of agents in the space. Before moving to their starting spots and walk, the generated turtles will be given their own speed, sight, tolerance, direction and destination.

Walk: When turtles are walking, this procedure will inspect the following factors in every step: whether the next patch is occupied by another turtle, whether the next patch is wall and whether the amount of surrounding turtles outnumbered its own tolerance. Any factor will trigger Avoid procedure.

Avoid: When the next patch is wall or occupied by another agent, the turtle will rotate a small degree to the left or to the right, then twice the same degree to the opposite direction until the next patch is accessible.

Under the above settings, the basic running mode is as follows: Set-human procedure will be triggered firstly. Instead of heading directly to the destination, turtles will randomly deflect a small degree to simulate the unfamiliarity. Before Walk procedure is triggered, turtles will check if the accessible reporter of destination is true, which makes turtles head towards their destination or keep the same direction. During walk procedure, walls or other agents may instantly trigger avoid procedure and change the direction of turtles. Turtles disappear after reaching their own destination. Through the running process, moving track of each turtle will be recorded for subsequent research.

2.2. SPACE SYNTAX THEORY

In the process of simulation, we find out that although properties of each unit of space can meet our demands, they are inadequate in describing the topology of the space, namely, the interrelation between space units. Consequently, the decision of the behavior pattern that an agent adopts is merely based on properties of an aggregation of some segregated space units that have weak interrelations (Jiang & Claramunt 2002).

Commonsensically, an individual who attempts to get familiar with some strange environments, such as figuring out the route to unfamiliar places, is inclined to get to nodes that provide with a greater perspective of overall situation.

In other words, an individual affected by this inclination tend to get to nodes that are easier to 'observe' other parts of the space, such as leaving for a square from a byway.

To simulate such an inclination in Netlogo, complex algorithm should be designed. As for space syntax, it is tractable in such situation on account of its capability of describing the topology of space. Thus, some of its analytical approaches and principles are apposite to import to the MAS, in order to ameliorate the behavior pattern of agents.

In our paper, Depthmap, has been utilized. After importing a digitized map of Gulou Square, a grid map can be converted that divides the whole space into an array of square space units (nodes). Then it can make visibility graph of the grid map as well as run visibility graph analysis. Subsequently, visibility relationships of the nodes are calculated.

Among the relationships, one concept, mean depth, is vital to our research. Alasdair Turner explained in his research that mean depth is calculated for each node much like the step depth (Turner 2004). The shortest path through the visibility graph is calculated to each other node with in the graph. These are summed and divided through by the number of nodes in the graph. Besides, integration is a normalized version of the mean death. The lower mean depth a node has, the higher integration value the node is assigned.

3. Case Study: Gulou Square

This research presents the simulation of pedestrian flows in the abstracted representation of the south part of Gulou Square in Nanjing, Jiangsu province. This square acts as an essential ingredient in the well-developed traffic system, located in the city center. The rich variety of space and height-changes brings in the possibility of view blocking.

The duration of the research was from winter of 2015 to late spring of 2016. The weather changes could be provisionally ignored as it only made a difference to visitors of recreational purposes, not the research samples who employed the square as a passing road. The research was carried out between 1 p.m. to 2 p.m. under the most situation. Data was gathered by means of over-all videoing and individual tracing, with sorting and selecting afterwards. Through data processing, people who were customarily coming for entertaining were ruled out. Moreover, the data will be compared with the model's output to assess the optimization of the model.

Figure 1 numbers each entrance/exit for the south part of Gulou Square. Based on the research data, several regulations have been sorted out as follows:

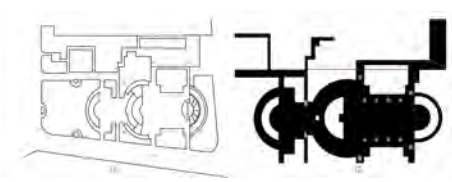


Figure 1. Gulou Square.

1. Pedestrians from entrance No.1 and 3 take an almost straight route passing through the square than exit from exit No.2, 5 or 6 and vice versa. Exit No.4 is usually out of consideration.
2. Pedestrians taking exit No.1 outnumbers those who choose exit No.3. The field research shows less trees near exit No.1 so the exit is clear in sight, indicating view blocking has the power affecting pedestrians' personal choices.
3. The route choice between exit No.2 and 4 are straight-lines. Because there is a public toilet beside exit No.4, people may choose this route out of strong and clear motivation.

3.1. APPLICATION OF NETLOGO AND DEPTHMAP

The first step of computer modeling is to make a digitalized map of Gulou Square. This research utilizes CAD to delineate Gulou Square, then converts it to a grid map in which each grid is given a value to be differentiated by Arcmap, and eventually imports to Netlogo (figure 1). Through such steps, the patches in Netlogo are set as an array of square grids with different values. Subsequently, they virtually become impassable walls (white part) and accessible areas(black part) and start or destination points of agents (grey part).

The second step is to set the properties virtual crowds. Values are set to be floating in a limited range so each property is a variable that affects the behavior of an agent. Thus, agents have different behavior patterns on account of the floating properties, which contain speed, sight, tolerance, destination and starting point (two points selected randomly by patches among six points). While processing the simulation, reporters will adjust some variables, including crowdity, distance and accessible to cope with different situation.

Nonetheless, the algorithm enhancement of the sight should be paid attention to. And the result of our quantification is Visual integration, calculated by Depthmap. A VGA graph reflecting the Visual Integration of each node of the space is shown in the following (figure 2). As the legend showed, the more a node's color approach red on the color bar, the higher value the node holds.We import the grid map carrying the value of Visual integration of nodes, as well as assign the value to patches accessible, expecting that agents are able to adjust their behavior according to the Visual Integration of the periphery.

With principles of the Space Syntax being added to, the program changes accordingly. When the accessible of an agent's destination is judged to be false, indicating the invisible destination, the agent will move to a node with the highest value of Visual Integration among nodes around it. Of course, an agent is set to avoid sharp turning while moving.



Figure 2. The visual integration model made by Depthmap of Gulou Square.

3.2. SIMULATION RESULTS

The research focuses on two contrast experiments with variable-controlling approach. The first contrast experiment analyzes the features of crowds' behavior patterns without the intervention of Depthmap when visual range and tolerance in Netlogo changes. In this experiment, we apply the average speed of pedestrian derived from field research, that is, 0.26 patches per period. And the speeds of many subjects are randomly set around the sub-average speed. Visual range and tolerance change the same way as in realistic field and become the major study objects since differences exist among individuals and the setting range of threshold value is large. Meanwhile, the second contrast experiment analyzes the differences in model simulations with and without visual arithmetic optimization through Depthmap, keeping all other parameters unchanged. This literature attempts to deduce the possibility of combining space syntax and multi-agent through scenario simulation.

Firstly, the research conducts the contrast experiment on visual range, 5 variables of which, 10, 30, 50, 70 and 90 are respectively chosen while other parameters remain the same. According to the basic information accumulated in the field research, the number of pedestrians is set to 50, velocity of pedestrians 0.26 and tolerance 7. Each pedestrian route is recorded in red. Below (figure 3) are the simulation results and analysis:

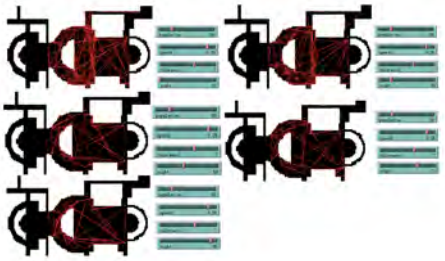


Figure 3. Simulation experiment: visual Range 10, 30, 50, 70 and 90.

It can be clearly seen that visual range has essential influence on pedestrian route. There is negative correlation between these two, which indicates that the smaller visual range is, the more pedestrian detours would take. For instance, if the visual range is set to 10, the over-dense pedestrian flow line indicates a variety of illogical detours. If the visual range is set to 30, the flow line becomes clearer while illogical detours still exist. There are more lines existing around the central white obstruction perhaps because it blocks pedestrian sight at the left-side entrance and exit. The simulation result has largely improved at visual range 50. The most logical situation emerges at 70, where pedestrian routes are clear enough and generate fewer detours. There are still more lines around the central white obstruction at visual range 90, which indicates that the parameter is inconsistent with and already beyond the actual pedestrian visual range.

Secondly, the research also conducts a contrast experiment on tolerance. This experiment applies the same approach as the previous one, keeping the population

size and speed parameters unchanged, setting visual range to the most reasonable range, 70, and picking up four values, which are 2, 4, 6 and 8 as tolerance parameters. Experiment results and analysis are displayed below (figure 4):

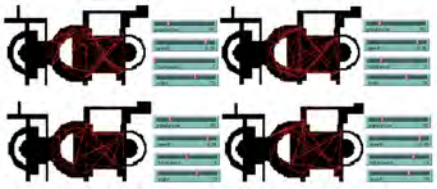


Figure 4. Simulation experiment: Tolerance 2, 4, 6 and 8.

It shows that the lower people's tolerance is, the more changes in routine in avoidance of congestion are, and thus the longer distance is. In our result, pictures with parameters of 2 and 4 present relatively complex routines and there are more branches from one point to another. This is because the tolerance range is too small (Notice that overlaps of routines in pictures are generated in different time other than coincidence at the same time). When tolerance is increased to 6, the flow line improves obviously and routines become concise. If tolerance continues to increase to 8, the situation is no big differences from that of 6, which indicates that tolerance values above 6 are proper and practical.

The second experiment contrasts model's simulation condition with and without Depthmap. In our project, we first study that whether Depthmap has effects on model's simulation under a visual range of 50 and 70 respectively (figure 5). And it can be observed from the comparison of these two groups that the application of Depthmap simplifies crowd routines and nearly eliminates wide-angle turnaround. This experiment demonstrates that Depthmap effectively optimizes the algorithm of subjective visual range in Netlogo and makes it more realistic.

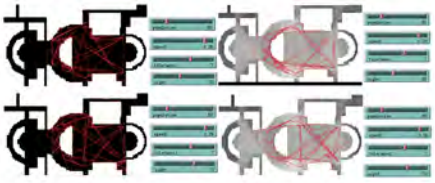


Figure 5. Contrast experiment: Visual Range 50 and 70. Left (without space syntax). Right (with space syntax).

In addition, this project provides specific analysis in terms of agent volume. In comparison of massive individual routines (figure 6), we find that space syntax makes no differences when there are no barriers between the starting and end point since pedestrians can see the terminal directly. But when there are a lot of barriers, the theoretical shortest routine is circuitous, space syntax enables pedestrians to predict the methods of avoiding barriers and move towards a more spacious direction. Furthermore, when the number of subjects gradually increases to 30, 70 and 90, model's simulation without space syntax becomes unreasonable (figure 7).

Faced with many barriers, turtle tends to walk directly towards them and make a big turn before collision due to avoid algorithm. But if turtle still cannot see the exit within new visual space, it will repeat previous action. Therefore, even though subjects make it to the end point at last, their routines are unreasonable for the repetitive actions of walking to barriers and then avoiding them. On the contrary, there are few curves in routines under space syntax and the main routines are in high coincidence. It can be inferred that Depthmap algorithm provides an optional routine after simulating routines between two points numerously. Though avoidance still appears occasionally due to the confinement of tolerance, in general, subjects all tend to the optional routine if any possible.



Figure 6. Contrast experiment: single routine. Upper (with space syntax). Down (without space syntax).

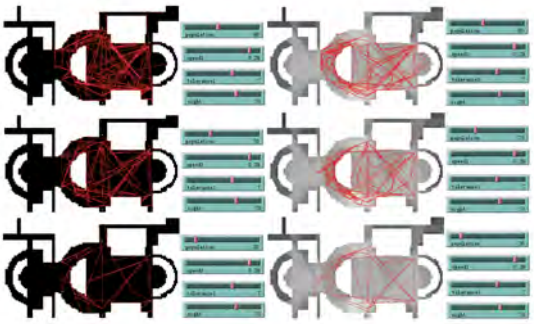


Figure 7. Contrast Experiment: The number of agents: 30, 70 and 90. Left (without space syntax). Right (with space syntax).

4. Conclusion and Discussion

After a long-played investigation, we gradually established models and completed parameters as well as algorithm in the project. Through massive simulations, we come to the conclusion that space syntax is able to improve crowd behaviors under complex open urban space. Space syntax can optimize individual visual range and is compatible with Netlogo which contains a sufficient number of complex environmental parameters. A combined application of Depthmap and Netlogo ensures the reasonability and logicality of model operation, leading simulation results to an accordance with the basic conclusion derived from our field research.

This simulation model hinged on reality is still a work in progress. Next steps

of this research will involve optimizing algorithm and setting more constrained parameters. The framework of this model will be broadened to these fields:

1. Optimize algorithm. The parameters will be designed more accurately, such as the range of speed and the operating principles of tolerance or sight. Moreover, the unreasonable interaction of these algorithm will be corrected.
2. Introduce environment parameters such as different weather conditions or micro-climate to the model and assess to which extent they can affect the outcome.

Acknowledgement

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MEASURING THE PERCEPTIVE INTRICACY OF THE CHINESE SCHOLAR GARDEN

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Abstract. The carefully orchestrated relationship between view and movement forms a core composition principle of Chinese scholar gardens to create poetic depth. We focus on one characteristic case study to examine the intricate spatial relationships between what is visible and what is accessible from the garden visitor's perspective. We examine the garden layout through a quantitative approach based on Visibility Graph Analysis. We identify a certain congruence between visibility and accessibility patterns, and propose that a network of strategically distributed overview spaces is employed throughout the garden to counterbalance tensions generated from disjunction between visibility and accessibility. The paper offers new insights into how quantifiable aspects of the garden can be used to generate qualitative perceptions of elegant restraint and compositional intricacy.

Keywords. Chinese scholar garden; Landscape design; VGA analysis; Overview space; Purview interface.

1. Introduction

The experience of visiting a Chines scholar garden has often been compared to a "stroll in a painting", which implies the simultaneous experiencing of visual and kinesthetic aspects of the garden. The relationship between view and movement is carefully orchestrated and forms a core composition principle consciously employed in the design of Chinese scholar gardens to create poetic depth (Li and Yeo 1991). Visitors to these gardens experience a disjunction between visibility and accessibility: multiple pathways and bridges, walls, openings, trees, winding waterways and rockeries create intricate layouts in which the directly visible is often not directly accessible (figure 1). The creative composition and disjunction of visibility and accessibility can be understood as a spatiotemporal art form that generates a rich variety of events and sensations involving encounter, discovery,

expectation and recollection, temporary disorientation and a return to the known while strolling in the garden (Bedingfeld 1997; Chen 1984; Lu 2010; Lu 2011). Chinese scholar garden design has previously been analysed and discussed primarily in analogy to pictorial art, and few attempts have been made to identify a coherent rationale in its compositional approaches. However, many sources also comment on a certain holism or unity that connects intricate spatial arrangements in the Chinese scholar garden, along with a general preference for the implicit, removed and ambiguous over the explicit and clear (Chen 1984; Peng 1986). In this paper, we attempt to capture and describe this holistic quality in the Chinese scholar garden by examining the relationship of spaces that are visually and physically accessible with a quantitative approach based on Visibility Graph Analysis (VGA).



Figure 1. Image of Chinese landscape painting and Panoramic Picture of Scholar Garden.

As a characteristic case study, we examine the Master of the Nets garden, a famous Chinese scholar garden located in Suzhou, China (Liu 1979). The garden has been documented to exist for almost nine centuries but has been rebuilt several times until the late Qing Dynasty (ca 1868). The garden covers an area about 0.5 hectares, and consists of two parts: the residential part and the garden, which constitutes four fifths of the compound (figure 2).

From a perceptual point of view, the garden is full of changes. The open-floor spatial organisation of buildings, numerous openings on walls, and constant interplay between that which can be seen and that which can be accessed form what has been described as scenes beyond scenes, and gardens within the garden, creating the effect of boundlessness while achieving a unity of part and whole. The garden is appreciated for its masterful handling of relative dimension, contrast, foil, sequence and depth, and borrowed scenery, which demonstrates the characteristic quality of Chinese garden design of synthesising art, nature and architecture (Chen 1984).

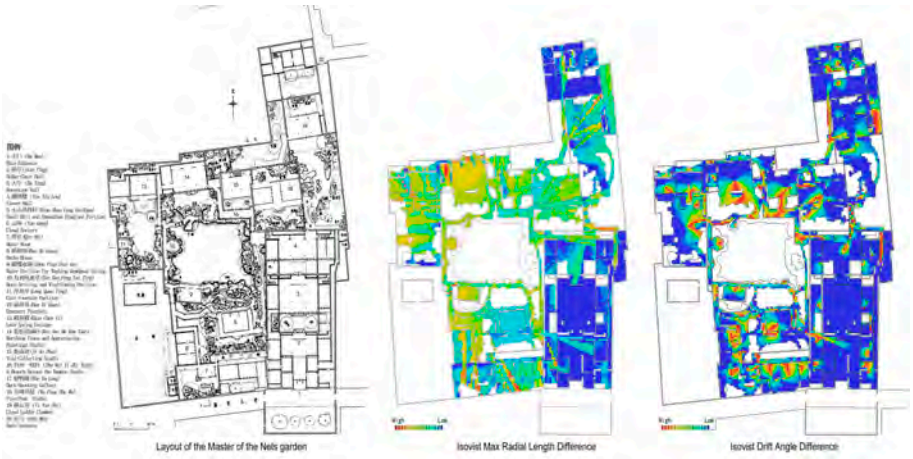


Figure 2. Layout of the Master of the Nets garden (Source: Liu 1979); difference between visibility and accessibility in isovist max. radial length (middle) and drift angle (right).

2. Methodology: Visibility Graph Analysis

The study employs Visibility Graph Analysis (VGA) of Space Syntax (Hillier 1996) analysis to investigate the spatial relationships between visibility and accessibility embedded in the garden layout. VGA was developed based on the concept of *isovists* as introduced by Benedikt (1979). An isovist or visibility polygon is the area visible or accessible from a given vantage point, in which all other points are directly visible from that point (figure 3). Benedikt argued that the geometric properties of visibility polygons could give insights into human perception and navigation of spaces as they capture the variation of visual fields experienced during movement (Gibson 1978).

Turner et al (2001) extended the measurement of properties of singular isovists into the configurational analysis of Space Syntax by describing the relationship of a position to all others in the analysed space according to the topological distance required to reach them. They developed a computer program called *Depthmap* to perform visibility graph analysis of plan layout, which models a plan layout into a grid system of point locations and represents the degree of relative connectivity of all the mutually visible locations across that system. Various measures and parameters taken from a combination of space syntax techniques and geometrical properties of isovists are then used to quantify both the local and global properties of point locations within an overall grid system. Some recent studies have focused on extending VGA analysis to overcome limitations of Depthmap resulting from not adequately capturing "inaccessible but visible" spaces, such as experimental studies in 2D layout (Taniguchi et al. 2012) and 3D environment (Varoudis and Penn 2015).



Figure 3. Visibility polygon of isovist (left); difference of isovists between visibility and accessibility shown in blue and red seen from a location (right).

Previous empirical studies have established that the visibility patterns of building layout influence different kinds of cognitive processes and behaviours (Peponis et al. 1990; Choi 1999; Yin et al. 2016). Extending these studies, Yu et al. (2016) applied VGA to analyse the perceptual properties of traditional Chinese scholar gardens, and suggested that the spatial transparency and ambiguity of the Chinese garden can be related to local visual isovists properties and global path structure.

3. VGA Graph Measures

As the scope of this paper is limited, we refer readers interested in key VGA notions to the previous works outlined in the previous sections, and concentrate here on analysis of the plan layout of the Master of the Nets garden through the *Depthmap* software. In order to capture the spatial effects arising from the disjunction between view and access, the garden layout is analysed through two separate spatial systems: the eye-level visibility map where only obstacles to direct views are treated as boundaries; and the knee-level accessibility map where anything blocking physical movement is treated as a boundary. In both cases, trees and furniture are omitted for preliminary simplification. While this may not address the garden in its multi-dimensional totality, it is well established that in contrast to Western gardens, Chinese gardens rely primarily on the placement of architectural elements for their compositional aims, with plants playing only a minor role (Bedingfeld 1997; Yang 1994). We apply a grid of 0.6x0.6m tiles to construct the VGA map of the case study, approximating human scale and step length. Only occupiable spaces bounded by the accessibility map are populated with grid tiles: accessibility and visibility map have exactly the same number of tiles; the difference is that their graph measures are computed using different boundaries to generate visibility polygons.

In the following sections, we compare the VGA graph measures of the visibility map and accessibility map as derived from the garden layout. The differences between the two systems are investigated to highlight the disjunction between the visible and the accessible that creates the spatial effects experienced in the Chinese scholar garden.

4. Measuring the Separation of View and Access

We first examine the degree of separation between visual and physical accessibility as seen from individual viewpoints, assuming that the geometrical properties of the visibility polygon can give insights into human perception of space. Figure 4 illustrates value differences between visibility and accessibility maps, visualising differences in a consistent colour spectrum of red to blue (showing values from high to low).

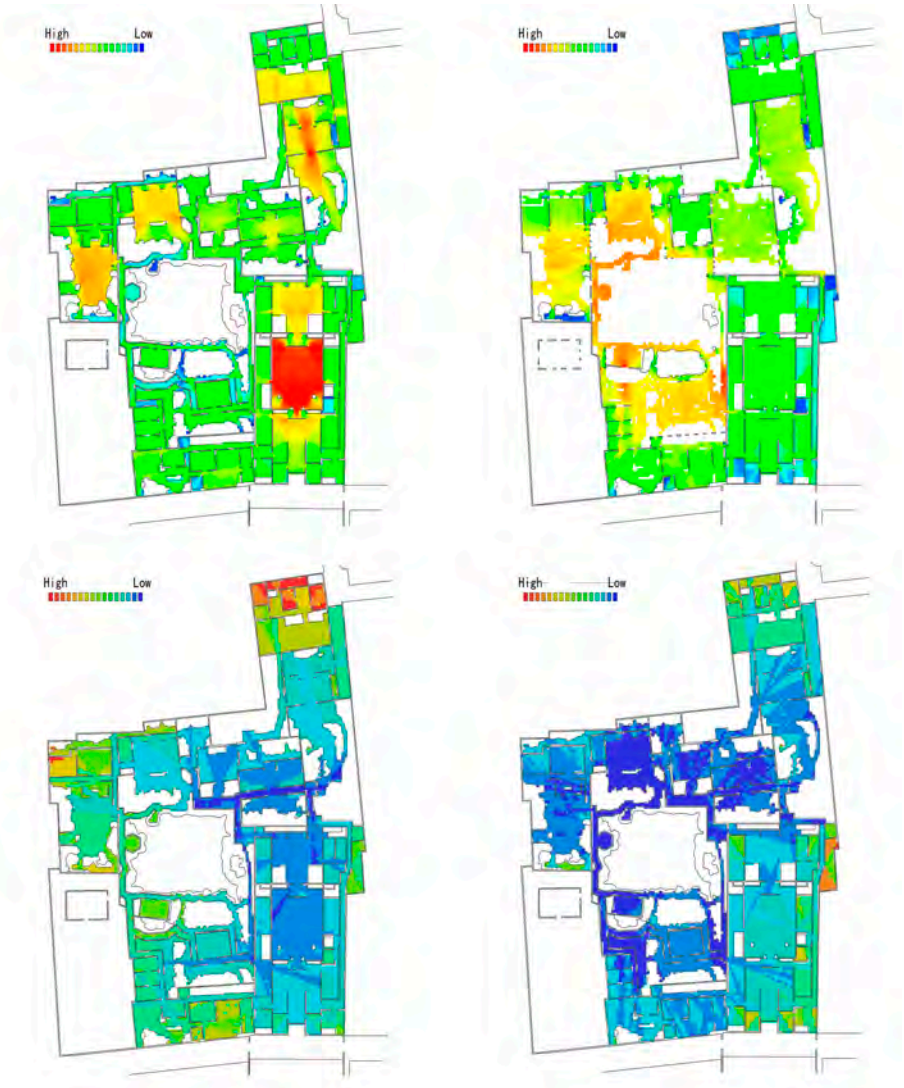


Figure 4. Comparison of direct purview (top row) and mean turns (bottom row) between visibility (right column) and accessibility (left column).

The spatial disjunction of view and access can be immediately observed in the direct purview analysis when comparing the visibility map with the accessibility map. The two maps display distinctive spatial patterns in terms of value distribution. In the accessibility map, direct purview appears to be strongly differentiated between high and low values. Spaces with strong direct purview are distributed in a more dispersed pattern, focusing on individual courtyard buildings and reaching a peak in the main reception hall of the residential quarter. On the other hand, values of direct purview in the visibility map have a relatively weak differentiation. When focusing on direct purview, a more centralised pattern emerges, which is dominated by spaces around the central pond and has little overlap with spaces that have strong direct purview in the accessibility map (figure 4).

The differences of global purview measured in mean turns between the two systems are also remarkable. The value of mean turns in the visibility map is only about one third of the value found in the accessibility map (1.91 vs. 5.41), which means the visibility map is much shallower and hence simpler than the accessibility map. In the accessibility map, lower mean turn values associated with spaces of strong global purview form a rather compact, inward-looking shape around the central quarters of the eastern part of the garden. In contrast, the visibility map features lower mean turn values radiating from the central pond and spread evenly through most parts of the garden except of the eastern residential house. Like the direct purview maps, the visibility and accessibility maps have little overlapping in terms of distribution of spaces with strong global purview. This clearly illustrates that the separation between visibility and accessibility systematically creates the spatially complex or even paradoxical situations experienced in the garden: that which you can see through but not walk through; while everything appears to be close it remains difficult to reach physically.

5. Symmetry and Circularity

We argue the association of syntactic property (measured in number of turns) with the metric property (measured in meters) in the accessibility system of garden is an important means to create the spatial effects and intricacy mentioned above. The twisting character of the access system of the garden can be shown with a simplified representation of the routes as a line system. As shown in figure 5, the route system has almost no dead-end path. Intersections of circulation are predominantly 3-way T-junctions, and cross intersections are very rare. There are many loops in the circulation system, but they are small in size and topologically deep in the sense of more than expected direction turns contained in each ring. Intuitively, the circulation system appears to be fragmented into many smaller and mutually interlocked loops. Walking further in the garden always means walking in circles, with constant route bifurcations diffusing path direction.

What can be inferred from this analysis is that the topological structure of the garden's circulation system is both circular and symmetrical when seen from any location within the garden. Here we find a different spatial logic from that of buildings and urban spaces examined elsewhere in space syntax literature, namely, the using of linear connection of space to reduce topological distance at the expense of increase of metric distance (Peponis 2012; Hillier 2003). The garden layout

minimises spatial differentiation in terms of linearity of space organisation, thus reducing the syntactic (topological) properties to the metric. The dominance of circularity, diffusion and symmetry in the circulation structure seems to generate perceptions of uncertainty, endlessness and maybe even disorientation. If the visibility system of the garden creates strong visual connections, then the circulation system seems to create the effect of corporal avoidance, where social co-presence or encounter happens more likely by chance rather deliberately.



Figure 5. Step depth analyses of the main entrance and a centre location showing the evenly distributed depth gain as a result of symmetrical and circular route system of the garden.

6. Spatial System

To examine more closely the relationship between spaces with strongest direct purview and spaces with limited purview in the accessibility map, we apply the concept of *purview interface* introduced by Peponis (2012). Spaces with the strongest direct purview (top 10% of all tiles) are defined as overview spaces. We analyse how far in number of direction turns or in metric distance other spaces are from these overview spaces.

About 80% of spaces in the garden are two or less turns away from the nearest overview space, and 35% of them are directly accessible (0 turn) from an overview space. The average number of turns to the nearest over-view space is 1.3, which is less than one fourth of the mean turns of all tiles. Moreover, the metric distance of 83% of all other spaces from the nearest overview space is no more than half of the mean distance of those spaces from all spaces. The average mean metric distance of all other spaces to the nearest overview space is 12.3m, which is less than one fourth of their mean metric distance from all spaces.metric distance of all

other spaces to the nearest overview space is 12.3m, which is less than one fourth of their mean metric distance from all spaces.

The average visual turns from other tiles to the nearest overview space is 0.37, of which nearly two thirds (65%) of other tiles are directly viewable from an overview tile, and one third are viewable by one eyesight turn. Based on these results, the garden layout can be understood more easily due to the proximity of spaces with limited direct purview to overview spaces that offer more extensive direct purview. Overview spaces function as a reference allowing a localised simplification of the complex spatial relations of the garden not only because they afford more direct connections but also because they are more powerful in synchronising relationships by access or by view. The overview spaces are well distributed, forming into local clusters with varied size and shape, and associated with different domestic functions. They are separated from each other and not inter-visible or inter-accessible directly from each other (more than 4 turns by walk and more than 1 turns by view). Unlike the findings of building analysis conducted by Peponis (2012), the garden does not seem to form a *continuous purview interface* or a *cognitive skeleton* (Kuipers et al. 2003) by linking the overview spaces into a network. Rather, the overview spaces of the garden function as discrete cognitive references. They are partially exposed to views and physically removed from each other. Their strategic distribution creates distance between them, both in terms of view and access. The spatial experience of the garden is synchronic and diachronic simultaneously: It is synchronic in the sense that the strategic distribution of the overview spaces brings with it the synchronisation of many relationships both in terms of view and access. It is diachronic in the sense that the cognitive reference offered by overview spaces fragments into local clusters hidden from each other, which shades the continuity of purview interface and makes trajectory perception of garden as a spatiotemporal event. In future, we are planning to follow up questions arising from our observations, such as whether the properties identified in our study can be intentionally planned, or under which circumstances they can arise.

7. Conclusions

While this paper focuses only on a limited aspect of the garden captured with VGA analysis, results offer a differentiated view on how it is possible to create simultaneously perceptions of ambiguity and subtle overall compositional order. According to our analysis results, a key aspect of the spatial organisation of the Master of the Nets garden seems to lie in the way eye-level visibility and knee-level accessibility are disjointed, creating a sensation of elegant restraint and allowing for various unexpected encounters. This perception of ambiguity and slight disorientation is counter-balanced by strategically distributed depth-compressing overview spaces. These spaces allow localised simplification and orientation within the intricate overall spatial networks. In general, organisation of the garden space as it appears based on the VGA analysis presented in this paper can be characterised as non-linear, often circular and networked in the form of interconnected smaller loops, embracing diachronicity and temporary order within larger ambiguous contexts. This characterisation resounds not only with previous descriptions of the experience of moving through a Chinese scholar garden, but also with composi-

tional principles typically found in classic Chinese landscape painting. As this type of space is difficult to describe in linear and deterministic terms, the type of analysis presented here may offer opportunities for qualitative design applications of a highly quantitative form of analysis.

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GENERALIZING EKPHRASTIC EXPRESSION

A Foundation for a Computational Method to Aid Creative Design

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Abstract. This paper presents the results from exploring the concept of ekphrastic expression as the foundation for a computation method to aid creative design. Ekphrasis or ekphrastic expression is the expression of a concept that is represented in one medium in another separate medium. The paper describes the concepts of ekphrastic expression and presents two implemented examples that demonstrate the method and produce new results. The first example involves the creation of new shapes through representing the shape designs in the evolutionary domain and introducing new operators within that domain beyond the standard evolutionary operators of crossover and mutation. The second example involves the creation of new genes to represent aspects of Frank Lloyd Wright's Prairie House style. This generates a space of genomes beyond those that were there at the commencement of the process. New designs that could not be directly produced in the original domain are generated.

Keywords. Creative design; ekphrastic expression; design method.

1. Introduction

Ekphrasis or ekphrastic expression, originally described by Plato in the *Republic -Book X*, is the expression of a concept that is represented in one medium in another medium. He used the example of a bed, which has three expressions: the physical object, the representation of the bed as an image, and the bed represented in another art form. It has been used extensively in the arts and literature such as when a scene from a poem is the basis of a painting or when a sculpture describes a dramatic event previously described in prose. This paper takes the idea of ekphrastic expression and applies it to design through its elaboration as a computational method to aid creative design.

In the arts ekphrastic expression involves the transformation of concepts represented in one domain into isomorphic concepts represented in another domain

(Fowler 1991; Goldhill 2007; Leader 2014). Take as an example the mythical story of St George killing the dragon, sourced to around the 11th century AD. The precise nature of the story and what it exemplifies is not of interest here. What is of interest is that the story is depicted in multiple other forms. It is expressed as a sculpture in figure 1 (left). The same story is expressed as a painting in figure 1 (right). This is an example of ekphrastic expression, where the nature of the domain of expression allows for different expressions. The story and its expressions are used as the basis of many characters and plotlines in video games.



Figure 1. The story of St George and the Dragon expressed as: a stone sculpture (left) and as a painting (right).

Ranjan et al. (2013a; 2013b) showed that the cross-domain interpretation of artistic ideas, i.e., ekphrastic expression, can be tested empirically and that such a cross-domain interpretation of artistic ideas can be the basis of some form of creativity.

The remainder of this paper introduces the concepts of ekphrastic expression more formally before presenting examples of implemented systems that produce designs that are novel or both novel and surprising through ekphrastic expression.

2. Ekphrastic Expression is Not Re-Interpretation in Design

In design we are familiar with the notion of representing ideas in different media and particularly so when we use computation since all computation is symbolic, i.e., we have transformed the design idea into symbols and those symbols are acted on not the design idea. Representation and re-representation have a well-established role in design and in computational models of design. Schon's reflective model of design is based on this representation and re-representation approach (Schon 1983). Many design models and methods have been constructed from this foundation (Damski & Gero 1994; Davies et al. 2003; Gero 1999; Jupp & Gero 2004; Karmiloff-Smith 1995; Kurtz 2005; Oxman 1997; Sperber 2000).

However, there are two significant differences between the use of ekphrastic expression as practiced in the arts and in design. First, we have a double ekphrastic expression in design. After we transform from the initial domain, d_1, into a second domain, d_2, we need to transform the results of the activity in domain d_2 back into the representation of domain d_1, which is the domain of the design. Second, we carry out processes in domain d_2 that do not necessarily have a counterpart in

domain d_1. The processes in d_2 are contingent on d_2 and are a consequence of the paradigm of that domain. The representations in domain d_2 offer affordances that are not available in the representations in the initial domain. The activity in domain d_2 may be capable of producing new and surprising concepts in domain d_1 and as a consequence can be considered the basis of a creativity method. Further, we can produce new processes in d_2 that generate completely new results compared to previous results in d_2 that are then transformed back into d_1. Thus, ekphrastic expression differs from re-representation as used in design.

The rest of this paper outlines the concepts of ekphrastic expression and presents two examples including an implementation that demonstrates the method and that produces new or new and surprising results. The first example involves the creation of new shapes through representing the shape designs in the evolutionary domain and introducing new operators within the evolutionary domain beyond the standard evolutionary operators of crossover and mutation. This generates a space of genomes beyond those that existed at the commencement of the process. The new genotypes are viewed as shapes in the original domain, shapes that could not be directly produced in the original domain. The second examples also commences with re-representation into the evolutionary domain but introduces the new evolutionary operator of genetic engineering.

Ekphrastic expression can be treated as both a design method and a framework for a class of design methods within which a number of existing methods can fit. As a framework it provides structure to determine commonalities amongst apparently different methods. As a method it provides an approach to the production of designs that may be creative (Miller & Mair 2006; Milligan et al. 2007). Any representation offers affordances and any change in representation offers new affordances that can be acted on to produce new behaviours and hence may potentially produce creative results (Gero & Kannengiesser 2012).

3. Formalizing Ekphrastic Expression

We commence by formally describing representation and re-representation. Then we describe ekphrastic expression formally building on these descriptions.

We can describe all computation, C, as being composed of representation, R, and processes that operate on those representations, P. This can be written as:

$$C = \{R, P\} \tag{1}$$

Designing computationally involves design processes, P^d, operating on design representations, R^d, producing designs, D. This can be written as:

$$D = \left(R^d x P^d\right) \tag{2}$$

Where all design representations are composed of elements, E, and relationships, H:

$$R^d = [E, H] \tag{3}$$

Re-representation involves a transformation process, T, applied to the original representation, R^{do} resulting in R^{dn}:

$$R^{dn} = T\left(R^{do}\right) \tag{4}$$

Hence, designs are produced by applying the processes associated with the original representation, P^{do}, to the new representation, resulting in new designs, D^n:

$$D^n = \left(R^{dn} x P^{do}\right) \tag{5}$$

However, in ekphrastic expression in design we have two phases, the first is the expression in a new domain and the second is the transformation back into the original domain. We can describe ekphrastic expression using the same symbols as we used to describe representation and re-representation.

Computation, designing computationally, representation and re-representation remain the same, except that the re-representation is in a new domain, *N*, resulting in R^{dN} and associated with this new domain are processes that substitute for the processes in the original domain:

$$R^{dN} = T\left(R^{do}\right) \tag{6}$$

In the first phase we have the added activity of substituting the processes that apply in the new domain, P^{dN}, where SP is a process substitution process:

$$P^{dN} = SP\left(P^{d}\right) \tag{7}$$

Designing in the new domain becomes:

$$D^{dN} = \left(R^{dN} x P^{dN}\right) \tag{8}$$

In the second phase we need to transform designs back into the initial domain using an inverse transformation operator, T^{-R}, to produce designs from ekphrastic expression, D^E:

$$D^E = T^{-R}\left(D^{dN}\right) \tag{9}$$

with the expectation that the designs produced through ekphrastic expression may not necessarily be the same as those produced without it. In this paper this concept is demonstrated:

$$D^E \neq D^n \tag{10}$$

Figure 2 illustrates these transformations and substitution graphically.

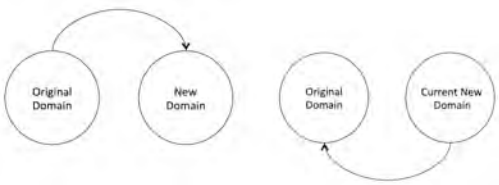


Figure 2. Left: Ekphrastic expression moves from an original domain to a new domain through transforming the representation in the original domain to those in the new domain and substituting processes from the new domain for those in the original domain; Right: a second ekphrastic expression occurs after designing in the new domain that moves the design back to the original domain through transforming the representation in the current new domain to those in the original domain.

4. Ekphrastic Expression Using Interpolation in Genetic Representation of Mondrian Paintings

Using Mondrian-like paintings we describe how the ekphrastic expression is formulated and show new designs derived from these images.

Here we present an example where the original domain is Mondrian-like images represented graphically, figure 3. The representation consists of rectangles, their colours and their topology.

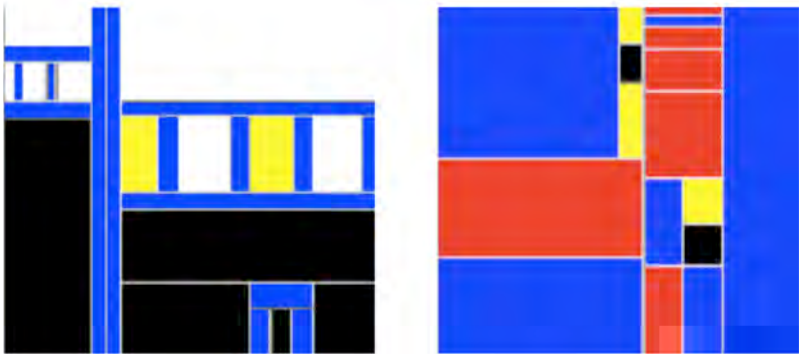


Figure 3. Two Mondrian-like images used as designs.

These elements and their relationships are the sets of variables that make up the representation of a design, R^{do}.

R^{do} = *[{rectangle, colour}, {topological relations}]*

Any design in this domain is the result of a rectilinear division process coupled with a colour selection, P^{do}, operating on R^{do}:

D^{do} = *([{rectangle, colour}, {topological relations}]* x *[{division, colour}])*

We now express this representation in the domain of genetics and transform the representation into genes, R^{dN}, and substitute the genetic operators crossover and mutation, P^{dN} for P^{do}. This gives us a gene space and a design space, which is the phenotype space in genetics, design space in design, and an expression process to transform the genes into phenotypes/designs (Bentley 1999). This results in:

R^{dN} = *[{genes}]*

P^{dN} = *[{crossover, mutation}, {expression}]*

We then add to the evolutionary processes of crossover and mutation available in genetics. We do this by commencing with Cantor's idea that "the real numbers are more numerous than the natural numbers". All evolutionary crossover and mutation processes work in the realm of natural numbers (integers) in that these operations only occur at the boundaries of genes. We asked the question what happens when crossover occurs not only at the boundaries of genes but also within them, i.e., real numbers not only natural numbers. This makes crossover a genetic interpolation process, a process that was not available in the original representation, figure 4. Any designs are now represented using an *F*-representation (Pashko et al.

1995) as real valued functions $F(x)$ such that $F(x)>0$ is inside the object, $F(x)=0$ is on its boundary and $F(x)<0$ is outside of the object.

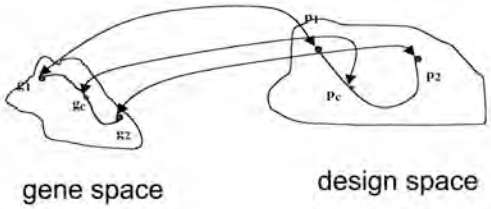


Figure 4. The process of interpolation between two parents results in a continuous path rather than a discrete path between the two parents in both gene space and design space (Gero and Kazakov, 1999).

We now have:

R^{dN} = *[{genes}]*

P^{dN} = *[{crossover, mutation, interpolation}, {expression}]*

As a consequence designs become:

D^{dN} = *([{genes}] x [{crossover, mutation, interpolation}, {expression}])*

We then transform the results in the new domain back into the original domain

$D^{E} = T^{-R}$*([{genes}], [{crossover, mutation, interpolation}, {expression}])*

thus, producing designs using ekphrastic expression.

We commence with the two Mondrian-like images shown in figure 3 as parents and transform their representation into the evolutionary domain. We then add the new evolutionary process that turns the trajectory between the parents into a continuous path. This produces a new domain that potentially contains designs that are not in the original domain. The original domain produces designs that are all composed of rectangles. Two examples of designs produced using ekphrastic expression are shown in figure 5.

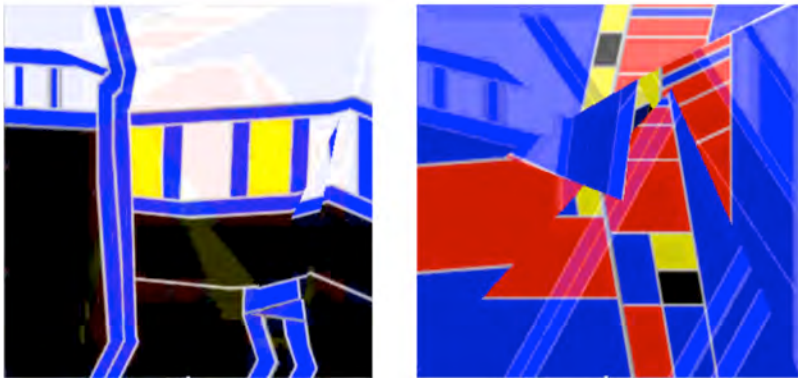


Figure 5. Two designs produced using ekphrastic expression in the evolutionary domain, transformed back into the original domain of shapes.

These designs contain the following elements that are not in the original designs:

- non-straight lines
- non-parallel lines
- triangular shapes
- rhomboid shapes
- "Z" shapes
- novel colours

The six elements listed above that appear in the design in figure 5 could not be produced by any combination of elements and topological results in the original domain. The original domain contained rectangular elements only and the topological relation of rectilinear division do not offer the opportunity to produce any other shape than rectangles. This demonstrates that ekphrastic expression - moving the representation from one domain to another, operating in that domain and moving back to the original domain - has the capability to produce results that are not able to be produced in the original domain.

5. Ekphrastic Expression Using Genetic Engineering in Genetic Representation of Frank Lloyd Wright Floor Plans

The representation in the original domain consists of spaces and their use. This is shown in figure 6 with the classes of space usage denoted by different shadings and different boundary line colours.

These elements and their relationships are the sets of variables that make up the representation of a design - a floor plan, R^{do}.

R^{do} = *[{rectangle, use}, {topological relations}]*

Any design in this domain is the result of a either a rectilinear division process or a combination coupled with a use, P^{do}, operating on R^{do}.

D^{do} = *([{rectangle, use}, {topological relations}]* x *[{[division, combination], use}])*

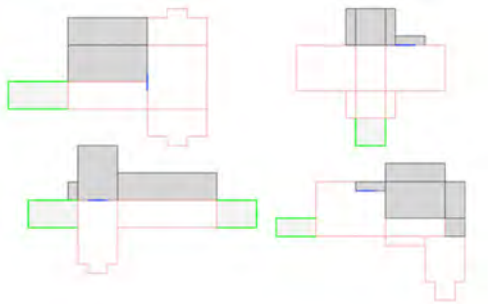


Figure 6. Four exemplary Frank Lloyd Wright Prairie House plans.

We now express this representation in the domain of genetics and transform the representation into genes, R^{dN}, and substitute the genetic operators crossover and

mutation, P^{dN} for P^{do}. This gives us a gene space of genotypes and a phenotype space in genetics, design space in design, and an expression process to transform the genotypes into phenotypes/designs (Bentley 1999). This results in:

R^{dN} = *[{genes}]*

We then add to the evolutionary processes of crossover and mutation available in genetics to get P^{dN}.

P^{dN} = *[{crossover, mutation}, {expression}]*

Here we add the new process of genetic engineering to the standard genetic processes, giving us a new P^{dN}. Genetic engineering is the process of locating gene structures in the genotypes of the high performing designs that are not in the low performing design, and then extracting that structure of genes and adding it to the gene pool. This results in both a change in the structure of the gene space and an expansion of the gene space and hence an expansion of the space of possible designs. The mechanics of this new process of genetically engineering genes can be found in Gero & Kazakov (2001). So the new process becomes:

P^{dN} = *[{crossover, mutation, genetic engineering}, {expression}]*

As a consequence designs become:

D^{dN} = *([{genes}]* x *[{crossover, mutation, genetic engineering}, {expression}])*

We then transform the design into the original domain:

$D^{E} = T^{-R}$*([{genes}], [{crossover, mutation, genetic engineering}, {expression}])*

Figure 7 (left) shows the results of genetically engineering genes from the four floor plans in figure 6. These are expressed in the domain of the original plans, i.e., as lines with colours that produce rectangles, not as bit strings which is the representation in the genetic domain. Using these genetically engineered genes we can produce new designs in the style of Frank Lloyd Wright Prairie Houses. A genetically engineered Frank Lloyd Wright Prairie House is shown in figure 7 (right).

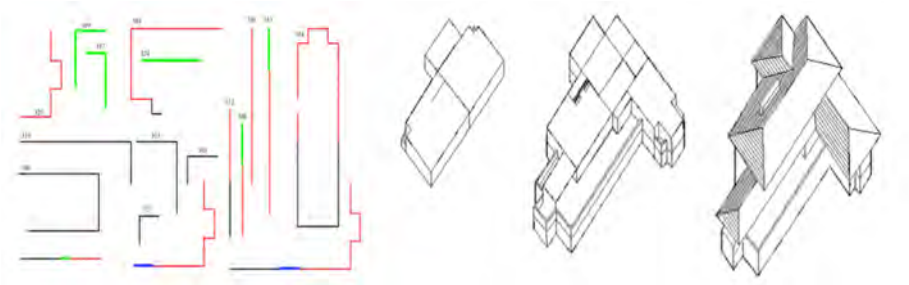


Figure 7. Left: Genetically engineered genes of Frank Lloyd Wright Prairie House floor plans. Right: A genetically engineered Frank Lloyd Wright Prairie House (after Schnier & Gero 1996).

6. Discussion

Ekphrastic expression provides a formalism within which we can represent the class of designing that involves not just re-representation in a new domain but also substitution of processes from that new domain for processes in the original domain. In this view re-representation alone is a degenerate form of ekphrastic expression. This approach provides a formalism for computational models of designing that involve re-representation and process substitutions. The example in Section 4 demonstrates re-representation into the genetic domain, use of the processes from that domain and the introduction of a novel process for that domain - interpolation. This produces results that are not predictable when examining the representation and processes in the original domain; specifically the original domain can only produce rectangular shapes but through ekphrastic expression non-rectangular shapes are generated. The example in Section 5 demonstrates re-representation into the genetic domain, use of processes from that domain and the introduction of a novel process for that domain - genetic engineering. This produces results that cannot be directly produced in the original domain of rectangular spaces.

We can view ekphrastic expression as a framework for an otherwise apparently disparate set of design processes that all share the common concept of moving to another domain where operations in that domain do not match those in the original domain, carrying out operations in the new domain and then transforming the results back into the original domain. At a foundational level we can consider the formal modeling in algebra or logic or even in a programming language of designs and designing as a form of ekphrastic expression.

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3D VISUAL SIMULATION AND NUMERICAL MEASUREMENT OF PRIVACY IN TRADITIONAL KOREAN PALACE

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Abstract. Traditional Korean architecture provides privacy through a proper balance of openness and enclosure through courtyard gardens. However, it is difficult to analyse privacy quantitatively in a three-dimensional space. The analysis of visual privacy is a significant issue in resolving conflicts and enhancing comfort. This paper develops a computational algorithm for simulating and measuring privacy on the concept of prospect and refuge: a design strategy for psychological well-being. In order to visualize privacy, the prospect area ratio (PAR) and refuge area ratio (RAR) are used in 3D visual simulations. PAR and RAR calculate the area ratio of the hiding space or the visible space in the images collected from the 3D model. In addition, parametric algorithms are proposed to calculate PAR/RAR automatically. Finally, this research demonstrates a case study of Gyeongbokgung, one of the five palace buildings in Korea, to show methods and processes of the quantitative analysis of visual privacy. The outcome of this paper contributes to quantitative confirmation of spatial characteristics that clearly distinguish between public space and private space of Gyeongbokgung. The proposed method also shows great potentials to quickly obtain the numeric value of privacy.

Keywords. 3D simulation; numerical measurement; traditional Korean palace; privacy.

1. Introduction

Privacy is a process of adjusting contact and approach distance with anoth-er person or a group (Altman 1975). This paper emphasizes that privacy is not a simple problem solved merely by blocking external instruction, but a dynamic process to optimally control over a level of access by others. Moreover, privacy is a subjective concept related to individual psychology, and it is also related to the culture and social environment of the individual (Lee 2014). Owing to these characteristics, it is hard to quantify property of privacy. However, it is necessary to optimize

visual privacy for the well-designed space. For the purpose of this paper, visual privacy is defined as the ability that a person can see others and can adjust interaction with the outside at any time without being observed by others outside (figure 1a). Visual privacy could be achieved through the adjustment of boundaries and territories in a physical environment (Kaplan and Kaplan 1989; Kelvin 1973; Newell 1995). This shows that visual privacy is connected to the prospect and refuge theory (figure 1b). This paper tackles computational simulation and quantitative analysis of visual privacy to get optimal design in terms of prospect and refuge.

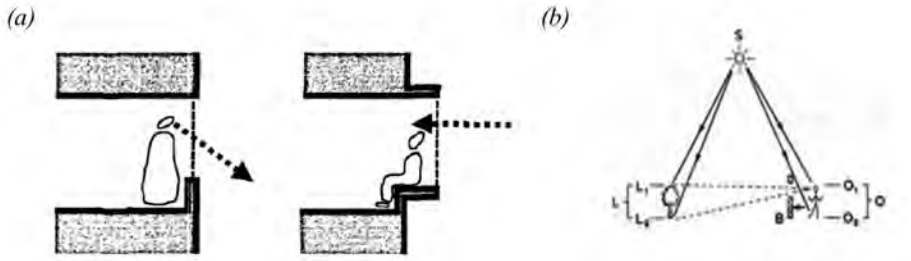


Figure 1. The representation of concept: (a) visual privacy (Al-kodmany 1999, p. 283), (b) prospect and refuge (Appleton 1975, p. 76).

Traditional Korean palaces represent the architectural style of Korea and play an important role in the study of history as the use of space is clearly divided according to the life of the Royal Family. These palaces regionally appear to have an obvious space configuration according to spatial function (Kim and Joo 1983). Typically, their spaces are arranged in order of in-creasing privacy from public areas of the palace entrance to private spaces at the back of the site: public areas, where national events and state affairs were held, and private spaces, where everyday activities such as sleeping and resting are performed. However, many architectural researches on tra-ditional Korean Palaces are focusing on qualitative analysis of their spatial, shape, color, material characteristics (Kim and Joo 1983; Yang and Cheon 2011; Chen et al. 2015). Because of the obvious space configura-tion according to spatial function by region in traditional Korean Palaces, considerable differences in visual privacy values are expected. In order to verify this, visual simulation and algorithms for numerical measurement of privacy are developed.

This research describes a method for visual simulation and numerical measurement of the spatial property of visual privacy, dealing with the dig-ital modelling which is involving parametric design. First, this paper ex-plains how to simulate visual privacy with the prospect area ratio (PAR) and refuge area ratio (RAR). PAR is the quantification of the ratio of the prospect area and RAR, the area ratios of concealed space, in 3D simulation. For the 3D simulation of PAR and RAR, exterior views looking into the inside from outside the space are considered to suggest a visual perception analysis method according to the walking paths. Second, in order to choose main paths and set observation points and view automatically, parametric values of are inputted. PAR/RAR calculating methods are developed

applying different parameter values for selecting main paths, the number and the heights of observation points and the view in observation points. In addition, parametric algorithms are proposed to calculate PAR/RAR automatically. Finally, this research demonstrates a case study of Korean traditional palace to show methods and processes of the quantitative analysis of visual privacy.

2. 3D Visual Simulation

In research by Dawes and Ostwald (2014), for spatial visual perception properties, the isovist area was quantitatively evaluated for analysis from the point of view an observer within that space. Lim et al. (2010) employed a visual access and exposure (VAE) model in order to quantify visual privacy from a random point within a space. While these researchers used 2D or 3D models and selected an observer point in indoor spaces according to perceived visual quantification, there was no consideration of the view looking into the inside from outside the space to evaluate privacy of buildings. Therefore, this research commences with the observer's view, taking into account the view from the outside of the building.

2.1. 3D MODELING

In the analysis of the overall characteristics of visual perception in 3D modelled buildings, it is essential to ensure a model's accuracy and practicable processing times (Bhatia et al. 2012). As there is a need for a high level of computing power to manage the data in 3D design, research on the actual application of the 3D simulation images is not much because of the software and hardware limitation. In response to the need for 3D visual simulation, Rhino (Rhinoceros 5) is used to provide a simple format of an architectural model. The buildings to be analysed for visual privacy are modelled in 3D using Rhino, leaving out intricate details such as decorations and textures. The shapes of the buildings are modelled considering general geometric properties, size, and building openings.

On the 3D model, main paths are suggested for walking through 3D buildings to set observation points (OPs). OPs are selected at regular intervals from the exterior to the main entrance of the building (for refuge area) or within the interior of the building (for prospect area). According to the path, images looking in or out of the buildings from the eye level of an observer (ex) 1.6 m) at each OP are captured and collected using the camera lens length (ex) 50.0) in Rhino.

2.2. 3D SIMULATION OF PAR, RAR

In the view from the exterior of a building into the interior, the indoor exposure area that can be seen through openings (doors and windows) is extracted. Within the entire image, after excluding the indoor exposure area, the remaining area is called the refuge area (RA), into which one cannot look. For images looking outward at OPs selected in the interior of a building, prospect area (PA) is extracted. As prospect is an unimpeded opportunity to see (Appleton 1975 in Stamps 2008) and the visual experience of subconsciously looking outward through openings (Kim and Kim 2004), the study includes everything to see as a prospect area with the exception of the buildings. Prospect area ratio (PAR) and refuge area ratio (RAR)

are calculated representing the proportion of PA or RA among all areas of view.

In order to visualize privacy in 3D simulation, rays at regular intervals are send from an observation point to target area surface (figure 2a). It is tried to select any rays transmitted through the opening into the inside of building for indoor exposure area (figure 2b). It is the RA that ex-cludes indoor exposure rays from all rays. On the other hand, for the PA, rays meeting a given building excluded from whole rays.

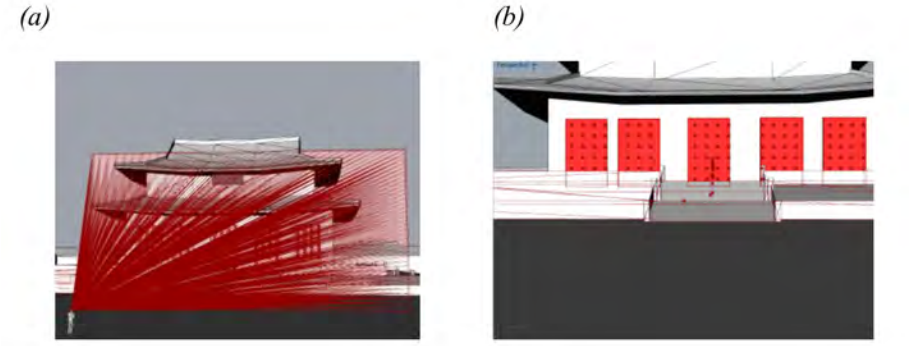


Figure 2. 3D simulation of RAR: (a) rays from OP (b) selection of indoor exposure area.

3. Numerical Measurement

This section provides the algorithms for numerical measurement of privacy using PAR and RAR in 3D simulation, and it is divided into three steps: selecting the main path and the observation points, setting view in observation points, automatically calculating PAR/RAR. These algorithms are developed with Grasshopper.

3.1. SELECTING THE MAIN PATH AND THE OBSERVATION POINTS

The first step involves constructing the grid which is used to create the observer points in the surface which the main paths pass over at the eye level of the observer (figure 3a). The number of grids and the height of observation point are used as parameters (figure 3b).

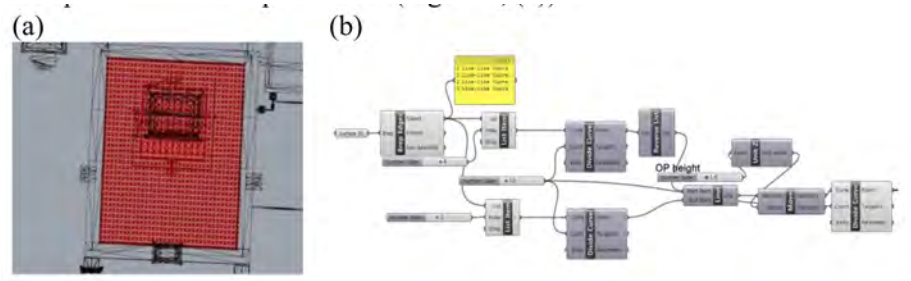


Figure 3. (a) Parametric definition of grid for setting observation point (b) Parametric values of grid.

In the next step, generating algorithm is developed in order to select an observation point on the grid. These points can be chosen at the grid intersection created above. Depending on the number of grid in the surface generated in the further stages, various distances between the observation points are also defined by means of parameters. Parameters located in uv domain within the grid. In addition, the main path is established automatically after selecting each observer point.

3.2. SETTING VIEW IN OBSERVATION POINTS

This second exploration with parametric design method involves setting view which accommodates any possible camera lens length, camera target point and camera view point. In the observation points, these parametric variables have settled view range of images.

In order to collect images looking inside the building from each observer point, each observation point is set as a camera viewpoint according to the main path. In addition to camera lens length, various horizontal distances between a camera viewpoint and a camera target point are defined by means of parameters.

3.3. AUTOMATICALLY CALCULATING PAR, RAR

To calculate automatically PAR and RAR, algorithms for trying to isolate rays transmitted through the opening into the inside of building and rays blocked on the building surface from whole rays are developed (figure 4).

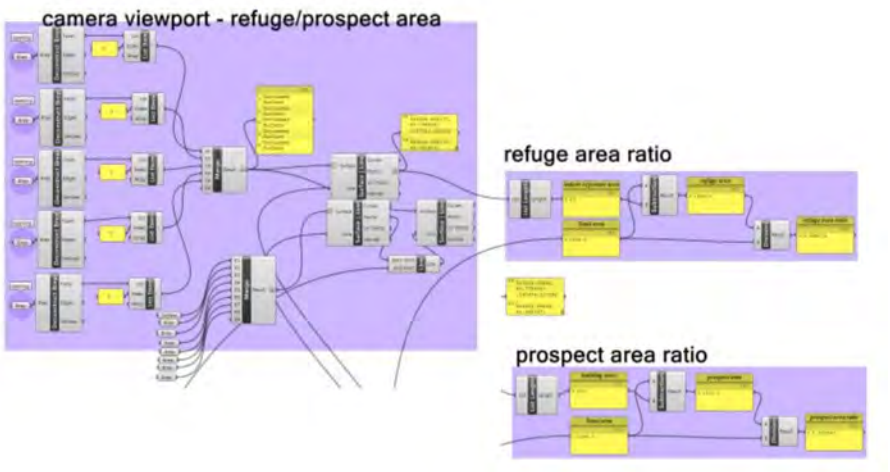


Figure 4. Automatic calculation of refuge area ratio and prospect area ratio.

4. Case Study

In this chapter, the verification process of the automatic calculation algorithm of PAR and RAR is described in a case study. Gyeongbokgung is selected for the verification experiment, which is the main royal palace of the Joseon dynasty located in northern Seoul, South Korea. It regionally appears to have an obvious

space configuration according to spatial function. In Gyeongbokgung, spaces are arranged in order of increasing privacy from public areas of the palace entrance to private spaces in the back: Geunjeongjeon as a public space, where national events and state affairs were held, and Gyotaejeon , which are private spaces where daily life occurred.

4.1. 3D VISUAL SIMULATION

Since royal palaces in Korea have complex forms and ornamentation, the lines that compose the forms are very complicated. Therefore, this study used Rhino (Rhinoceros 5.0) to provide a simple building shape for the palaces in our 3D models, based on the 3D spatial information on the Vworld. Vworld is spatial information open platform which the Korean Government built to provide 2D and 3D spatial infor-mation of Korea (Vworld 2016).

4.2. NUMERICAL MEASUREMENT

When the parametric values are inputted in the proposed algorithm, the RAR values are automatically calculated. Table 1 shows parametric values and inputted value to measure RAR in this case study. The comprehensive graphs of calculating RAR results describe the quantification of RAR in figure 5 and figure 6.

Table 1. Parametric values and Inputted values.

Parametric Value			**Inputted Value**
Observation point selection			
OP^1	Number of observation point	The number of grid	24
OP^2	Height of observer	Z coordinate	1.6
View selection			
VS^1	Camera view point	Observation point	1-24
VS^2	Camera target point	Distance between view point and target point	1.5
VS^3	Length of camera		50
VS^4	Number of ray for visibility	The number of grid intersection point on the target surface	36*36=9001296

Overall, the progressing aspect of the graph for RAR shows weaker levels of refuge closer to the building. The maximum value for RAR of 1.00 denotes that the interior of a building is not visible from the exterior, while lower values represent that the interior is largely exposed to the exterior.

In the analysis of refuge areas visible from the main regions of Gyeongbokgung, the level of RAR is generally high in private areas, and its average value is close to 1.00. On the other hand, public spaces have lower values to a certain extent compared to private spaces. As shown in figure 5 and figure 6, in Geunjeongjeon of Gyeongbokgung, the RARs along the path relatively suggest substantial variation (RAR=0.94→0.26). On the other hand, Gyotaejeon, the private space of Gyeongbokgung shows a refuge-dominant area. By the time the visitor approaches the gate, the main building finally could be seen with continuous declining the value of RAR (RAR=0.88→0.56).

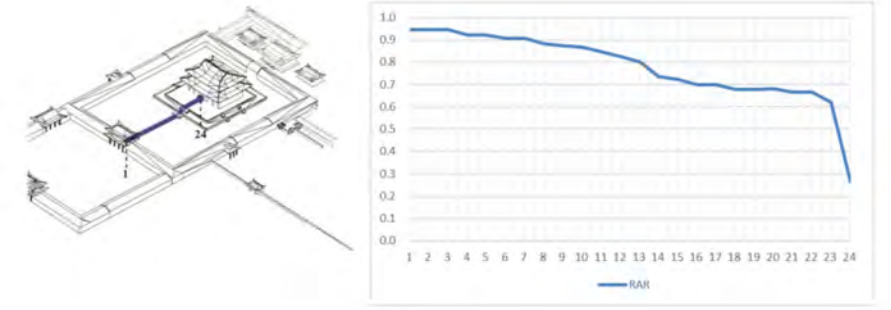


Figure 5. Refuge Area Ratio (RAR) graphs of Geunjeongjeon.

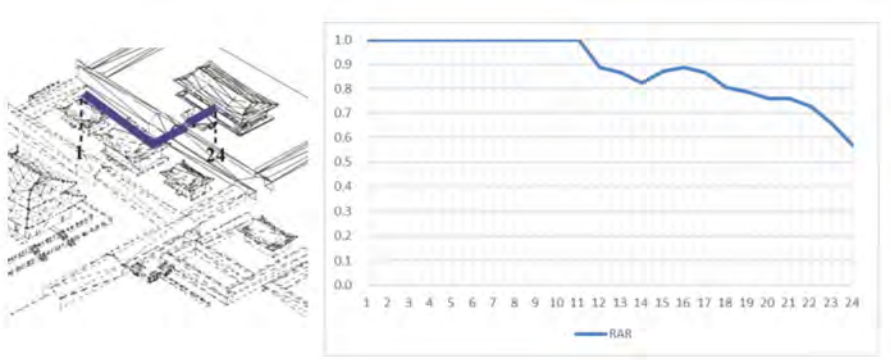


Figure 6. Refuge Area Ratio (RAR) graphs of Gyotaejeon.

Table 2. Prospect Area Ratio (PAR).

		Observation Point		
		1	2	3
Gyeongbokgung				
Geunjeongjeon	Front	0.3	0.2	0.22
	Back	0.03	0.02	0.03
Gyotaegeon	Front	0.04	0.04	0.04
	Back	0.02	0.01	0.02

By comparing quantitatively analysis of PAR resulting from 3D models in table 2, it shows the rate of area could be seen from inside to outside, excluding buildings. The level of PAR is shown to be slightly higher in front of Geunjeongjeon than in the back, since the back of Geunjeongjeon are relatively more blocked by walls and other buildings while providing extensive courtyard in front of these buildings. It means that visibility is provided in the front view of public spaces. On the other hand, since Gyotaegeon are rather adjacent to and closed by other buildings as a private space, it illustrates low level of prospect both front and back of the buildings.

5. Conclusion

This paper investigates the integration of computational simulation and quantitative analysis of visual privacy to get optimal design in terms of prospect and refuge. The method of simulation is developed for automatic measurement of PAR and RAR using different kinds of parametric values. This research presents an integration of two different digital tools: Rhino, Grasshopper. They are used to develop algorithms for setting 3D visual simulation and automatic measurement of PAR and RAR.

5.1. CONTRIBUTION

The greatest significance of this study is increasing usability by introducing 3D visual simulation and parametric algorithm. In 3D models of buildings, experimental research could be conducted without being constrained in time and without disturbances from surroundings. As a result, higher accuracy rates and time-saving are achieved, as there is no limitation on obstruction of visitors, constraint approach and weather restrictions in real time.

The proposed parametric algorithm in this paper has great potentials to quickly obtain information about the results of evaluating visual privacy at multiple points. Therefore, one of the most important outcomes of this study is providing an algorithm for designers to evaluate visual privacy for optimal control in the early design stage.

5.2. ISSUE

An issue that was not addressed in this study is whether RAR and PAR are absolute values that represent the amount of privacy. Nevertheless, since the proposed approach can quantitatively indicate the change of visual privacy according to the actual view along a path, it is expected to be very useful when planning spaces to provide privacy in the future. Moreover, in this paper, there are issues of investigating only front view and one main path with one case. This is the beginning of attempts to quantify the visual privacy of spaces using the concept of prospect and refuge; future studies that evaluate visual privacy quantitatively using various views and paths are expected with the algorithms of numerical measurement and automatic calculation.

5.3. APLLICATION

As this study commenced with Palace case study, the proposed algorithm needs to be more elaborated through another case study. More broadly, this research will serve as a base for future studies that this image analysis method of PAR and RAR could be applied to a wide range of architectural planning and design: a residential, healthcare and other buildings in which visual privacy is significant.

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INVESTIGATING VISIBILITY PROPERTIES IN THE DESIGN OF AGED-CARE FACILITIES

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Abstract. This paper uses a Space Syntax approach - a computational and mathematical method using graph-based measurements - to undertake a comparative assessment of the visibility properties of three architectural plans with unusual spatial requirements. Specifically, the method is used to compare the spatio-visual properties of an idealised plan for a residential aged-care facility with the actual plans used for two facilities. The purpose of this analysis is to begin to examine the ways in which syntactical values and isovist properties can be used to capture spatial and social characteristics of plans designed for the physical and cognitive needs of an ageing populace. The application of this approach seeks to support a better understanding of the relationship between spaces and their social properties in the design of aged-care facilities.

Keywords. Visibility analysis; Space Syntax; spatial cognition; social property.

1. Introduction

Since the 1970s, a growing number of computational and mathematical methods have been developed for optimising various aspects of architectural space planning. For example, Space Syntax methods (Hillier and Hanson 1984) have been used for predicting patterns of pedestrian movement, improving surveillance, reducing crime through observation, and understanding access and control issues. While many of these approaches have been embedded in contemporary software tools, and are in use in commercial architectural practices today, there are surprisingly few applications to assessing spatial and social properties in environments which are dominated by single age groups. In particular, the problems of an aging population - including social isolation, mental health and limited physical mobility - have rarely been considered using these methods.

The most challenging factors in the design of retirement villages and aged care centres include isolation, loneliness and confusion, all factors associated with spatial visibility (Gardner 1994). A capacity to understand an environment and socialise in it, both of which rely on levels of visual connectivity, are critical for the design of successful aged-care facilities. But equally, carers and nurses in these environments need to be able to monitor residents, but not constantly invade their privacy.

This paper, therefore, aims to present a computational analytic framework to capture visibility properties from the perspectives of different user groups and spaces. For verification purposes, the framework is applied to compare the properties of three plans, the first being a hypothetical or idealised plan, based on theorised medical and social needs (Eastman 2013) and the second and third are recent Australian designs identified by the International Association of Home and Services for the Ageing (2014) as representing recent industry practice. However, the primary purpose of this paper is not to analyse or criticise the three designs, but rather to begin to consider which aspects of the syntactical computational method will be most significant for assessing a building type which has unusual social and cognitive challenges.

This paper firstly investigates computational approaches to visibility analysis which affects the cognitive and social properties of architectural plans for residential aged-care facilities. A discussion of various methods and techniques and an application of a visibility analytic framework to three architectural plans are then presented. This paper concludes with a discussion about the results and the need for future research.

2. Literature Review

Research into the relationship between people (and their behaviours) and spaces (and their properties) is at the heart of several major theories of architectural analysis and prediction. In particular, environmental and behavioural research (Hayward and Franklin 1974; Nasar and Jones 1997; Stamps 2005a; Stamps 2005b; Sadek and Shepley 2016) identifies that enclosure is an important property of an environment, because it limits or shapes movement and perception. Multiple theories have attempted to explain how these spatial properties shape human responses and social interactions. For example, Appleton's habitat theory and prospect-refuge theory (Appleton 1975) are two of the most well known in architecture. Gibson's ground theory (Gibson 1950; Gibson 1979) and Kaplan and Kaplan's information theory (Kaplan and Kaplan 1989) are also used to explain human responses to space. Such theories use psychological, verbal constructs to analyse environments and because of this, their results are not always reproducible (Stamps 2005a) and they can be difficult to apply in architectural planning. Furthermore, these theories tend to assume that human responses are relatively universal (or at least that statistical patterns can be derived from them that reflect universal tendencies). While there is statistical evidence to support the general use of several computational methods for modelling and understanding socio-spatial properties of plans, relatively few examples exist of attempts to accommodate the needs of particular demographic groups. These issues are developed in this literature review section

which has two parts. The first briefly examines the computational methods that are conventionally used to analyse visibility in architectural plans and the second examines the application of these methods to healthcare facilities or those for residential aged care.

2.1. ANALYTIC METHODS

The two most common computational approaches to visibility analysis in architectural plans involve graph-based abstraction techniques, typically associated with syntactical approaches, and isovist based techniques or viewshed analysis. These two are also combined in visibility graph analysis (VGA).

For the first of these approaches, the properties of an architectural plan are typically abstracted into a set of nodes and edges in a graph, which can then be mathematically analysed. This method can reveal the relationship between spaces and the social properties which necessitate or sustain such relations (Hillier and Hanson 1984). Two of the common approaches to spatial analysis using graph theory are convex and axial maps. Convex maps allow for the analysis of programmatic spaces and their connectivity, conceptualised, respectively as nodes and edges, while axial maps capture behavioural characteristics including movement potential. An axial map is defined as the set of the longest lines of sight or movement that pass through and connect all of the habitable spaces of a plan (Hillier and Hanson 1984). Using graph mathematics, various quantitative, mathematical descriptions of the built environment can be derived from convex and axial maps. These include connectivity (the number of direct connections to other lines or spaces), integration (the normalised mean depth being compared to D-value) and intelligibility (the correlation between connectivity and integration). Connectivity describes the mutual relationship between all lines or spaces, while integration values indicate how well one space is connected to all others in a system (Hillier and Hanson 1984). It has also been suggested that integration values - including local and global integration - can be used to shape the design of healthcare facilities. Guney (2007) argues that "visibility structures work together with and enhance permeability structures" and both influence how an environment functionally spatially, as well as how it is experienced and understood.

The second major approach to plan analysis, isovist analysis, has been linked to the work of Tandy (1967), an isovist is defined as "the set of all points visible from a given vantage point in space" (Benedikt 1979, p. 49). The properties of the isovist's geometry or construction can then be measured. Past research has identified the mathematical properties of isovists that have potential correlations with human spatial perceptions. For example, Stamps (2005a) argues that several isovist properties - Horizontal size, Boundary permeability, Variation in distances to boundaries, Concavity, Boundary predictability, Elongation - can influence behaviour. Dawes and Ostwald (2014a; 2014b) highlight five isovist properties - isovist area, radial line, length, occlusion and drift - which possess a level of correlation with empirical research and Dosen and Ostwald (2017) demonstrate a statistically significant correlation between measures and perceptions of spatial exposure and enclosure. Franz et al (2005) note that the different spatio-visual analytical approaches used in architecture also correlate closely with the major

models of spatial cognition.

The set of isovists in a plan is the 'isovist field' and the relationship between isovists in a plan can also be conceptualised and measured as a graph. Thus, syntactical and isovist methods come together in visibility graph analysis (VGA) (Braaksma and Cook 1980; Turner et al 2001). Because both syntactical and isovist approaches have various levels of empirical support, VGA analysis seems to offer the potential for developing insights into the design of buildings that have particular visibility requirements.

2.2. APPLICATIONS TO HEALTHCARE FACILITIES

A growing body of research suggests that the spatio-visual properties of physical environments have an impact on a variety of health-related outcomes (Seo et al 2011; Haq and Luo 2012; Sadek and Shepley 2016). Because of this, various computational methods have begun to be used in the analysis or optimisation of health facilities, including nurses' behaviours (entries to patient rooms and spatial positioning, walking patterns), patients' preferences and satisfaction (preference for bed privacy, perceived quality of care), and visitor movement in hospitals (Haq and Luo 2012). For example, Seo et al (2011) investigate the impact of hospital unit design focussing on nurse behaviour. They suggest that the characteristics of routes from intensive care units (ICUs) to patient rooms and medication areas contribute to behavioural patterns. Setola et al (2013) study the role of spatial layout in hospitals and analyse the integration of both public and staff spaces. The research captures the patterns of relationships between patient and medical staff (P-M) through the density of interactions and accessibility maps. Lu (2010) measures the structure of visual fields in nursing units and Lu et al (2009) develop a targeted visibility analysis that is correlated to distribution of people and their interactions within an intensive care unit. Carranza et al (2013) present a spatial position tool with paths and interactive diagram with a low complexity isovist algorithm for assisting health design. They measure healthcare effectiveness through visibility, accessibility and contact between caregivers and patients. Sadek and Shepley (2016) classify a series of variations of Space Syntax tools for use in healthcare facility analysis including Target Visibility Analysis, Spatial Positioning Tool (SPOT), Weighted Isovist Area, Multi-Layered Network, Place Syntax, and Team-Base and Peer Distances. Such tools effectively demonstrate the usefulness of analysing spatial characteristics in terms of the perspectives of patients, visitors and staff. However, despite these valuable lessons, almost all of these examples are concerned with hospitals, not residential aged care facilities.

Research into the design of residential aged care facilities has gradually noted a change occurring in the way they are planned and has also developed a series of ideal solutions. For example, Brawley (2006) classifies two types of residential aged care plans; the older, 'double loaded corridor' variant, and the newer, 'race track' variant and Eastman (2013) offers an ideal design for residential aged care, taking into account medical and social research. Brawley (2006) argues that the planning of these facilities has evolved over time in response to research into the challenges of ageing.

A VGA analysis of Brawley's (2006) two plans (figure 1) identifies the syn-

tactical values of her two different aged-care planning types. Curiously, they have similar levels of holistic integration (5.03 and 5.06), although the race track variant has higher levels of connectivity (6.18.63 > 516.89) and commensurately higher intelligibility because of this. As such, the race track variant could be regarded as providing a higher level of cognitive clarity in the space, which might respond more effectively to the needs of dementia patients. However, beyond such general observations, large scale VGA analysis of this type is not especially revealing. Nevertheless, following Sadek and Shepley's (2016) lead, a more focussed analysis of VGA and isovist data, from the perspective of different user groups and spaces, could be more useful. This approach is taken in the next section.

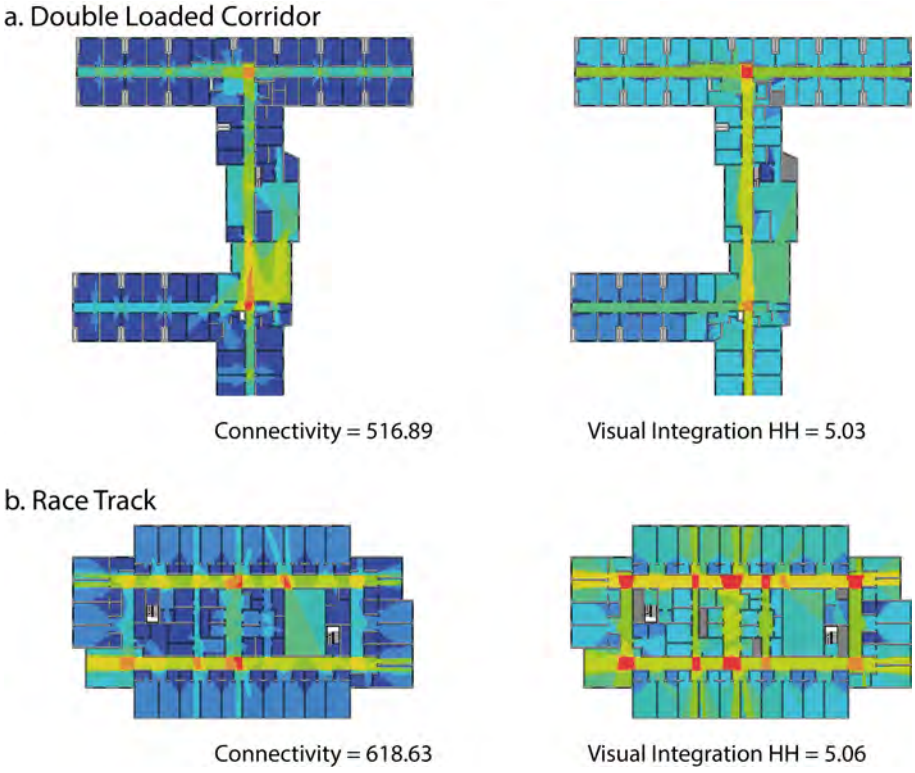


Figure 1. Connectivity and visual integration of two building typologies.

3. Case Study

The planning of three aged-care facilities is examined in this section. The first is derived from Eastman's (2013) ideal plan for an assisted living, group residence. The other two plans (Au1 and Au2) are contemporary Australian designs published in 'architecture for an ageing population' by International Association of Home and Services for the Ageing (2014) (table 1). All three cases are designed for a special care residence as well as a skilled nursing care. They are all multi-level buildings

for special care residents, although the second Australian case has a bigger site and building area. Thus, the comparative study in the next section uses mean values of measures from observation points to allow for more useful comparisons to be made. Importantly, the ideal plan has no site constraints whereas the other two do.

Table 1. Two Australian cases.

Name	Au1: Nambucca Head UnitingCare Ageing	Au2: Port Macquarie UnitingCare Ageing
Project type	Special care residence/ Skilled nursing care	Special care residence/ Skilled nursing care
Location	Nambucca Heads, NSW	Port Macquarie, NSW
Site size	3,853 m^2	14,677 m^2
Building footprint	1,921 m^2	3,635 m^2
Building area	5,463 m^2	7,225 m^2

3.1. APPLICATION AND RESULTS

The methodological framework used to analyse the three plans is VGA. It is applied in two ways.

1. Measurement of mean results for each plan for visual integration, isovist area, isovist perimeter, drift angle, drift magnitude, maximum and minimum radial and occlusivity. These measures provide a holistic indication of various spatial properties of the plan.

2. VGA analysis of isovists centred in four selected locations in each plan. The four locations are: visitor lobby, staff kitchen and common area, corridor from the perspective of nurses' viewpoint and corridor in residential units from a resident perspective.

For the first of these approaches, table 2 indicates the mean values for spatial properties of each plan. Interestingly, the visual integration value for the hypothetical case (H1) is higher than the Australian designs (3.61 > 2.84 and 2.54). This might be because the hypothetical plan has no site constraints. In general, a higher integration value represents a shallower or more assessable space (Hillier and Hanson 1984). More dramatically, HI has a mean isovist area which is more than double that found in Au1 and Au2 (88.48 > 36.40 and 35.33), although its isovist perimeter is only in the order of 20 - 30% more (61.74 > 48.45 and 47.50), and the drift magnitude (often described as 'strength of enticement' or 'visual pull') is of a similarly higher level of difference. The mean occlusivity measures are notably similar across all three plans, meaning that they possess a similar level of mystery or a similar capacity to hide (23.40, 23.39 and 22.48).

Table 2. Mean values of spatial properties (H: Hypothetical case, Au: Australian case).

	Visual Integration	Isovist Area (m^2)	Isovist Perimeter (m)	Isovist Drift Angle	Isovist Drift Magnitude	Isovist Max Radial	Isovist Min Radial	Isovist Occlusivity
H1	3.61	88.48	61.74	179.34	4.23	15.59	1.03	23.40
Au1	2.84	36.40	48.45	181.07	2.91	11.47	0.60	23.39
Au2	2.54	35.33	47.50	177.98	2.87	11.43	0.56	22.48

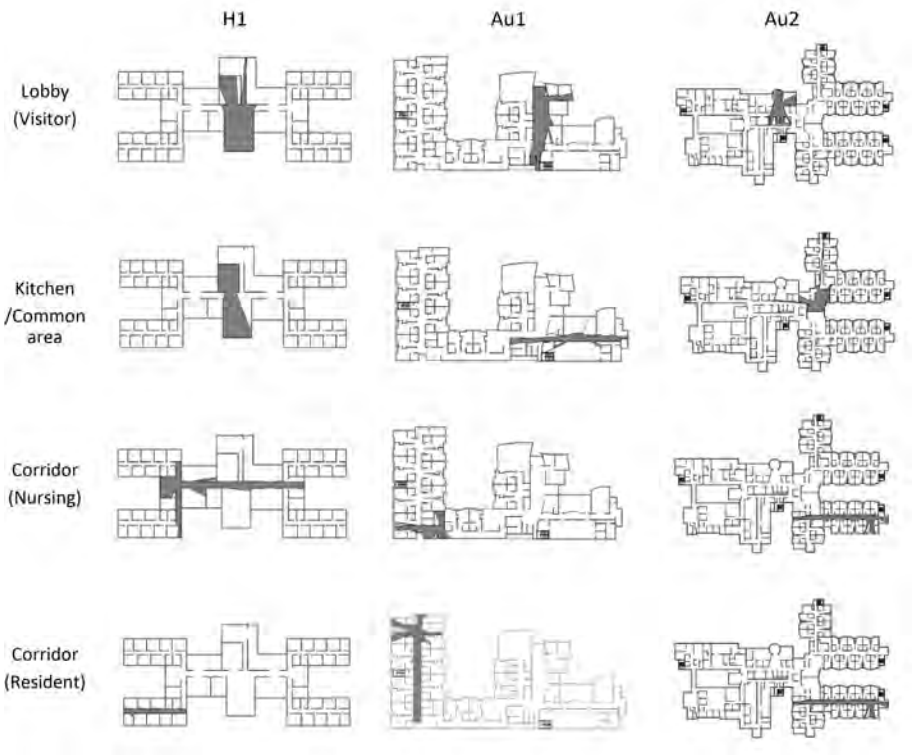


Figure 2. Isovist maps from four selected points.

For the second of the analytical approaches, isovists were examined in four locations in each plan (figure 2). Four properties - area, perimeter, max radial, and occlusivity - are measured and compared for each location (figure 3). When charted, these results reinforce some of the interpretations identified in the holistic examination of the plan, but they also point to several particular differences. One obvious example of this is seen in the chart for isovist area, which confirms that H1 does feature a large volume of visible space in the visitor's lobby, the kitchen and the nurses' station, but in the resident corridors, the three are similar. However,

isovist perimeter, which was on average higher in H1, is revealed to be less significant when examined from the perspectives of staff, nurses and residents. Only the visitor lobby has a significantly higher perimeter in H1. The results for occlusivity in H1 and Au1, broadly conform to the contemporary idea that lower levels should be present in the nursing station, than in any other area. Thus visibility should be clear for the Nurses. However, this is reversed in Au2, where the most visually commanding space is the kitchen.

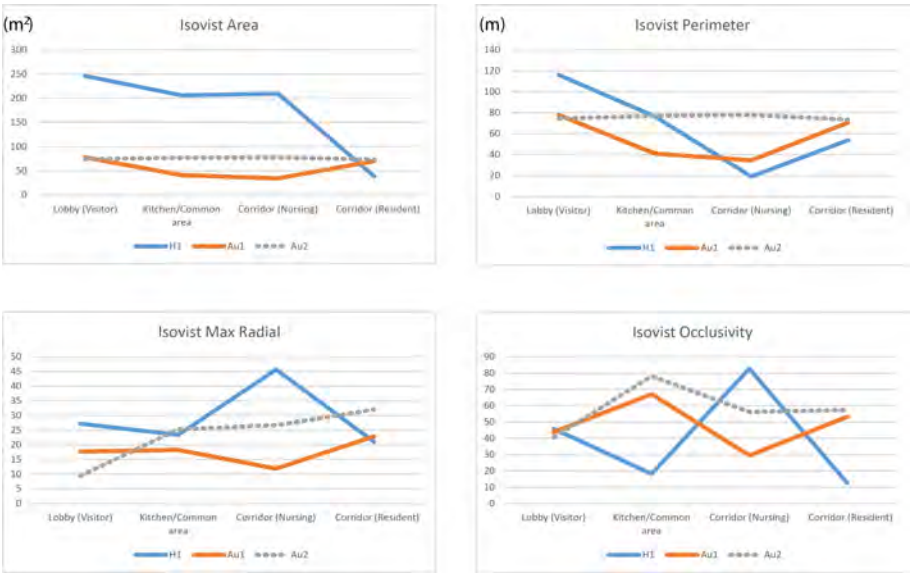


Figure 3. Isovist properties from four selected points in each case.

4. Conclusion

This paper takes a step towards the much larger process of exploring the planning of residential aged care facilities and the computational methods which are most appropriate for analysing their visibility properties. The paper describes an analytic framework for investigating the syntactical values and isovist properties of different spaces in aged care facilities. The framework is demonstrated through a comparative study between an ideal, hypothetical design and two designs produced by commercial practices in Australia. All testing was undertaken using a combination of architectural plans, geometric data and software.

The initial results indicate that the framework allows the investigation of integration values and isovist properties of the main functional spaces. It also enables the capturing of spatial and social characteristics in the design of aged-care facilities. Interestingly, the hypothetical design (H1) has the highest integration value as well as the biggest isovist area and perimeter, meaning that it is both well connected spatially and has a large (relative to the other two designs) volume of visible space from most positions. The results also indicate the viability of using these measures

to differentiate between spaces in terms of their visibility properties. This computational approach contributes to advances in fundamental knowledge in terms of environment and behaviour in aged care settings. A future study addressing the relationship between spatial configuration and social cognition is planned by the authors with more cases and with cultural differences in designs.

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BREATHABLE WALLS

Computational Thinking in Early Design Education

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Abstract. This research categorizes the different breathable wall systems designed by students and describes their potential. Also included is a discussion of the results of both the physical analyses and digital simulations of these students' designs. To optimize the environmental performance of each proposed system, this work also engages in a more specific discussion of the advantages and limitations of these designs. Finally, this research concludes with a summary of the evidence of the benefits and risks of employing simulation tools in architecture studios.

Keywords. Breathable Wall System; Computational Fluid Dynamics (CFD); Physical and Digital Wind Simulations; Architectural Prototype; Responsive Architecture.

1. Breathing in the Heart of the Desert

To better understand the combined effects of wind direction, pressure, and speed on a building in the heart of the United Arab Emirates, in the spring semester of 2016, first and fourth-year architecture students at Texas A&M University were asked to think holistically about an entire building envelope system for a small information tourist center. By becoming involved in the development of an integrated building system called a "breathable wall," students were asked generally to utilize environmental resources within their ecological limits, and specifically to explore the behaviors of wind on and around their designs (figure 1). In the proposed information centers, designing with a full understanding of breathability was vital; it affected the overall indoor air quality of the structure, as well as the thermal performance of the building.

The breathable wall system and information center project was based upon the concepts of sustainable living, respect for nature, energy savings, and resources streamlining, as a means of enhancing humans' relationship with a surrounding environment vulnerable to high temperatures, water scarcity, and strong winds carrying sand.

Far from the theoretical speculation often discussed in courses related to the environment, this project informed architecture students of possible ways of designing breathable wall systems for use in the hot desert climate of Dubai in the U.A.E. In a desert environment, once a mixture of air and sand touches the outer face of a porous wall, breathability becomes not only about the ability of that wall to allow the indirect passage of clean air through, but also its capability to prevent the transmission of sand.

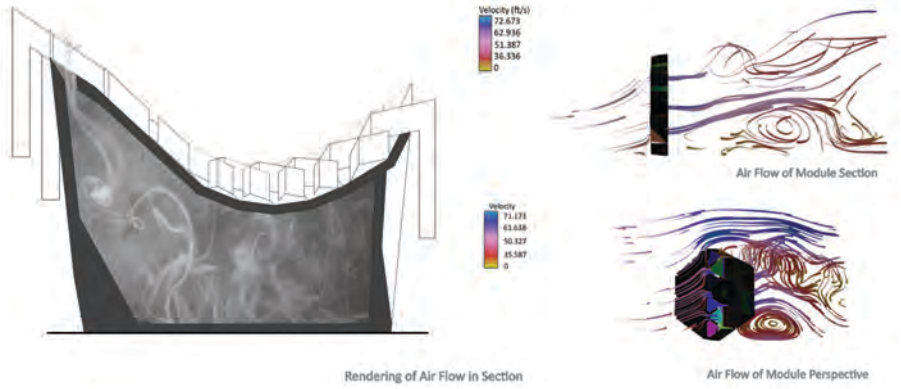


Figure 1. Wind simulations of the breathable wall system and tourist information center. (Simulation by Ashlyn Wilt & Esteban Armenta).

Students first considered various types and mechanisms of breathability and their consequences by reviewing traditional ventilation systems in hot, arid areas such as the Persian Gulf and North Africa. As a cross-disciplinary design activity, the Breathable Wall Project provided an opportunity to experiment with various designs for different porous and permeable building skins that purify air as building "lungs" when sandstorms occur. The goal was to design a self-shaded, self-ventilated, and self-cooled building envelope by integrating a natural ventilation concept into the building's body, in order to achieve a simpler, more robust, and less energy-consumptive system in a very hot and arid area.

Wind exerts positive or negative pressure on the exterior walls of a building. In this project, students attempted to consider the effects of both global and local wind pressures on their designs. At the same time, their designs' dynamic responses to wind loading were not neglected. Therefore, some of the proposed projects were not passively static in their interaction with wind as a dynamic phenomenon. For instance, in one proposed breathable wall, wind-induced force primarily produced a dynamic mechanical response in the breathable wall's components by changing the local wind direction and its distribution patterns. Another proposed strategy benefited from wind pressure along a windward wall surface to activate clusters of truncated pyramids when subjected to very strong winds. In this case, more like organisms, the small apertures of the proposed breathable wall were not expected to remain open or closed at all times (figure 2).

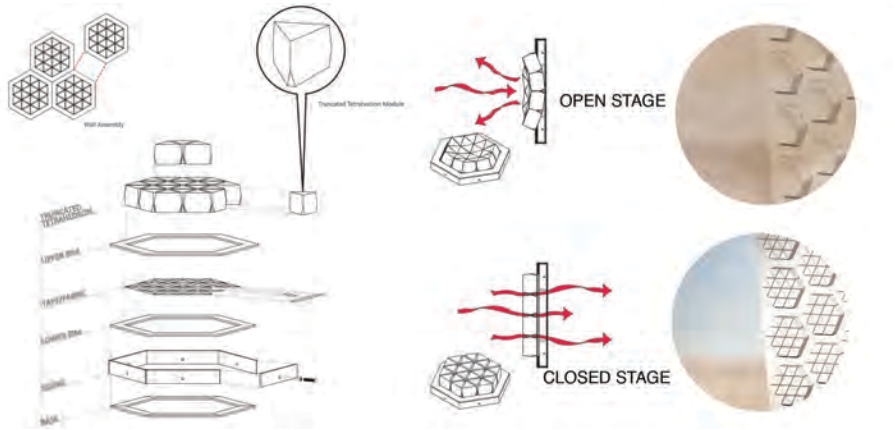


Figure 2. This aperture design dynamically responds to the wind pressure: it closes itself when the wind pressure is high (Drawings by Ashlyn Wilt & Esteban Armenta).

Functioning as either a static or non-static ventilation system, the breathable wall system had to satisfy the following criteria:

- Get fresh air into the building and exhaust air out;
- Block sand from penetrating into the building;
- Redirect the air upon entering;
- Cool down the air as it travels through the shaded zones; and
- Prevent light from directly entering the space.

In this project, although breathability refers to air currents and not moisture, to raise occupants' comfort level, running water along designated paths was proposed as a means of adding humidity and cooling the air as it passed over the modules (figure 3).

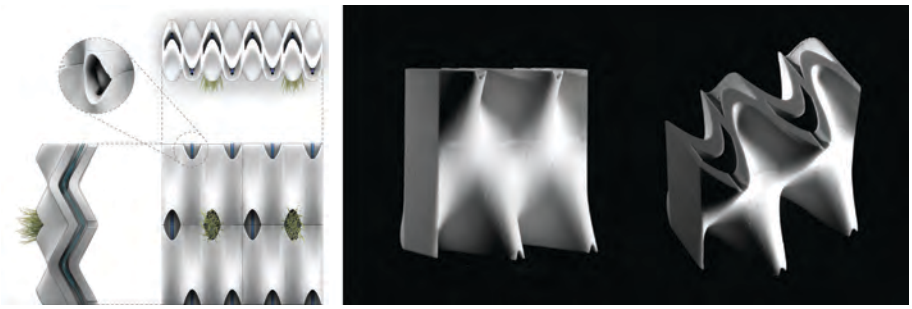


Figure 3. For raising the confront level, a student added water running into the wall cavity to cool down the hot air (Designed by Garrett Callen).

Since the trapped sand can clog openings in the wall, lowering its breathability, one emphasis of this project was sand collection. It was important for students to think about how to prevent sand from getting trapped inside wall cavities. To dispose of the collected sand, students developed a variety of approaches such as

escape holes and gutters. In some cases, disadvantages of the breathable walls were connected to dust, insects, or water infiltration.

2. Hybrid Physical and Digital Simulations

Understanding the environmental behaviors of a building subjected to high sandstorms is critical to developing less dependence on complex mechanical ventilation systems. Both groups of students in two studios were iteratively introduced to the tools and methods of designing, fabricating, and testing their permeable prototypes, in ways that provided conditions of comfort by altering wind flow patterns and speed.

Since the breathability of a wall is interrelated with the pressure inside and outside of that wall, students used both physical and digital simulations to study the pressure difference between the front and rear sides of their breathable walls. By incorporating a small-scale wind box test and Computational Fluid Dynamics (CFD) simulation software into the design process (figure 4), students were able to utilize these powerful tools to explore their concepts in the early design stage, rather than to simply represent and validate their final designs (Kirkegaard et al. 2008). Receiving feedback from wind experts (including academics and practitioners) helped students to comprehend the consequences of various scenarios relating to the constituent elements of their breathable prototypes.

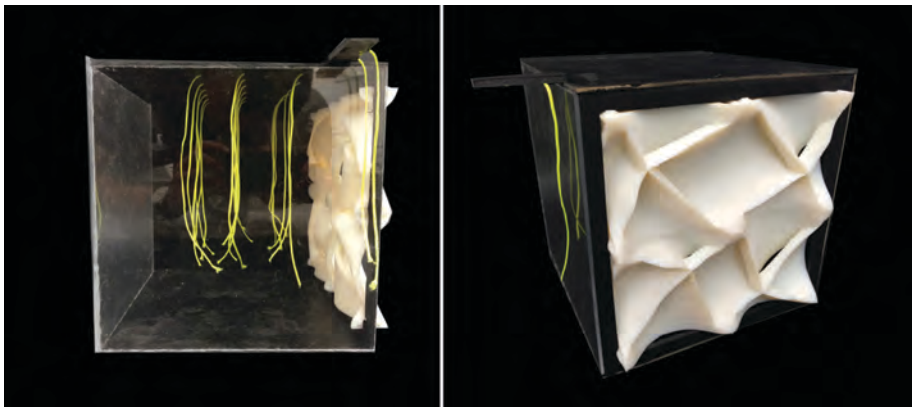


Figure 4. By using the wind box, students examined how the wind actually traveled through their designs (Christian Roose's 3D printed prototype was located in front of the wind box).

For students, the payoff of using both physical and digital simulations was significant. By considering some basic laws and principles of physics to understand the motion of sand, both methods of simulation helped students to develop genuine solutions based upon more than simple guesswork and speculation.

3. Empirical Analysis

The Breathable Wall Project also helped students to run different experiments focused on the analysis of small sections of a larger model or observations of large-

scale wind behavior in spaces near buildings. A broad range of these breathable wall designs were assessed by many factors that, in part, examined how the form and related dimensions of a breathable wall could empower it to meet its function. In this project, to evaluate the performance of potential design options, the simultaneous use of simulation software and physical wind testing expanded the virtual design environment back into the physical realm. For example, further physical experiments (such as erosion tests) were conducted to confirm the results of the simulations when wind flow was modeled by using particles on a dark-colored background. To this end, the project provided the opportunity to examine the limitations of physical wind box tests and these simulation tools when used by freshman and senior architecture students. To satisfy conditions related to occupant comfort, students evaluated the wind mitigation capacity of their designs after comparing the physical and digital simulations to one another.

As mentioned, the wind box was used in physical experiments to evaluate the sand blowing onto the breathable walls. The wind box was a stiff, rectangular box open at one end. As a wind source, a hair drier with different speeds was used to move the individual sand grains and blow them towards the box. Different breathable walls were placed at that end of the box, facing outward, through which a mixture of high-speed air and sand was passed. Sand dunes in a variety of shapes and sizes were formed by different wind velocities passing through the breathable wall. Measurements of the sand transported by wind inside the box were used to evaluate the performances of different designs. Some of the breathable prototypes were rigorously tested as a means of recognizing less successful breathable walls with higher sand transportation rates. After comparing students' design potential to their experimental observations, it was found that their expectations did not overestimate the performance of their prototypes in reality. Although they were also supposed to conduct a smoke test to confirm the permeability of their designs, this test was canceled due to limited time.

4. CFD Simulation Early in the Design Cycle

Computational Fluid Dynamics (CFD) programs have not typically been handled by architecture students. Only a short time ago, these programs were left largely to specialists with extensive backgrounds in simulation. The lack of immediate opportunities to acquire knowledge about how airflow actually circulates presented a major barrier, keeping students from understanding how their designs would perform in wind.

The Breathable Wall Project examined both Autodesk Simulation CFD and Autodesk Flow Design, two free pieces of wind analysis software. Simulation CFD is more accurate, but Flow Design is more user-friendly during the early design stage. Therefore, students mainly used Flow Design to examine the wind's effects on their breathable walls and the flow conditions around their information center buildings. Unlike common high-end simulation software that struggles with the speed and simplicity of setting up boundary layer conditions, solver types, or meshing resolution prior to creating simulations, Flow Design is an easy-to-use CFD software with little or no preparation required (Schmitz 2014). As a virtual wind tunnel software package, Flow Design is an excellent tool for instantly visualizing

how the wind interacts with a building and its components at the conceptual design level.

5. Flow Simulation Software in a Design Studio

Before students' designs were fully completed in Rhinoceros, flow simulation enabled them to avoid mistakes that would otherwise go undetected until the later stages of design development. Flow Design were chosen as a preliminary simulation tool for the studios. By helping them easily detect where and why mistakes were made and assisting them in dispelling those errors, Flow Design allowed for an in-depth exploration of ideas and fostered more critical and future-forward thinking.

By allowing them to play with different model configurations, Flow Design helped students examine diverse design strategies for transporting air through their designs while simultaneously excluding sand. One student remarked that "the purpose of this project was to design how wind would go through our modules so we were able to simulate it through Autodesk Flow Design. The program was very helpful for showing how the wind actually does travel through your design. It showed how wind does go in and comes back out slower and colder" (Madera 2016).

Students designed different breathable wall systems by using Flow Design. Below, several of these systems are described:

5.1. SYSTEM I

By far, the most significant transportation of air is attributable to either pressure or temperature differences between two locations. To benefit from different pressure conditions, most students designed inlet and outlet openings in their walls. Offsetting the locations of inlets and outlets allowed warm air to be redirected into a connected shaft; upon exiting, the air was cooler. The correct shaft angle controlled the air flow away from the interior and towards the ground. By using Flow Design, students studied how the sizes of inlets and outlets and the angle of shaft between them affected air speed (figure 5). For example, students noticed that air velocity decreased when the outlets were smaller than the inlets. One student explained the role of the simulation software in the development of her breathable wall modules, especially with regards to how she drew air from larger openings and funneled it through various shafts. "Using Autodesk Flow Design, I was able to see how air behaves as it passes through the module. Based on these results, I concluded that a more drastic angle is necessary to create the wind flow and direction I was hoping to achieve" (Ritter 2016).

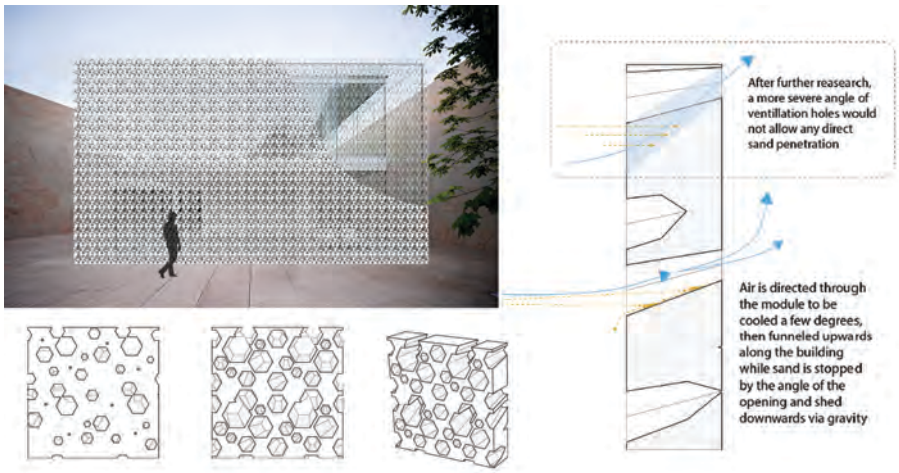


Figure 5. Students studied how the sizes of inlets and outlets and the angle of shaft between them affected air speed (Drawing by Sydney Ritter).

5.2. SYSTEM II

In order to create a funnel-like effect, some students used two segregated panels with intake and outtake apertures. Adding space between the panels slowed down the air speed. In addition, the gap forced sand particles to drop to the bottom, where they could then be collected (figure 6). Flow Design helped students studied how sand and air traveled throughout the space between the panels. Based on their outcome, one student remarked: "What I have learned from the analysis is that my design worked only slightly as well as I had hoped. While the wind did enter the holes and slow down, it had a tendency to go around the unit instead of through it. This means that in a full-wall system it would go around the building like we normally see, instead of being filtered through the space" (Higgins 2016).



Figure 6. Adding space between the panels slows down the air speed (Drawing and simulation by Kristin Higgins).

5.3. SYSTEM III

In order to control the amount of air flow, other students designed small barriers placed at the back of their modules. Besides affecting the air flow patterns, the placement of these barriers helped lessen the amount of sand entering the inside. One student stated: "The first barrier I had created for the sand was not effective enough. Therefore, I redesigned the piece to have a back plate that acts as a second barrier for the sand (figure 7). This reduces the amount of sand that penetrates the structure. The piece was then tested using Flow Design. It assessed how wind flow would behave with the design I created. Overall, the wind velocity slows down and escapes only through the gaps I have created. The second barrier connected to the core of the piece allows for wind to slip through, but not the majority of sand" (Mengers 2016).

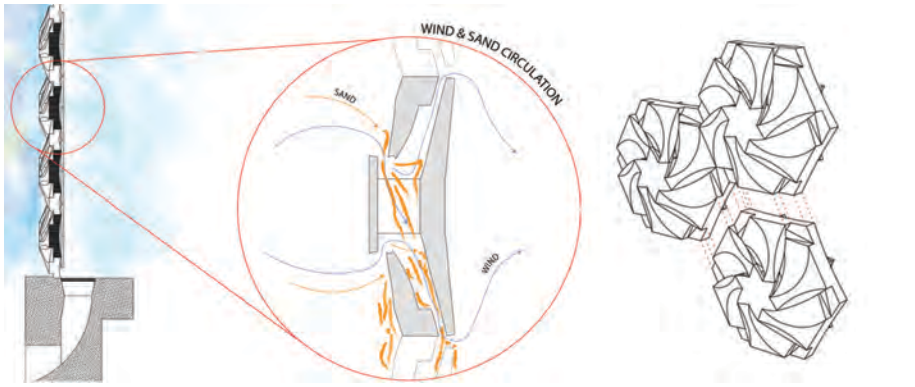


Figure 7. Digital wind simulation helped students to improve their concepts in the early design stage (Simulation and drawing by Chloe Mengers).

After importing the geometry, students were able to change its orientation. Since the size of the wind tunnel was adjustable, they could interactively change the air speed in the simulation model to quickly visualize the flow results and predict the behavior of their design. Although Flow Design offered students a chance to easily simulate airflow conditions in their "in-process" designs through the software's pre-selected methods, it was not able to analyze any other fluid flows (Tara 2014). In addition, this simple and fast program was not not as accurate as other CFD software (such as ANSYS Fluent), but easier and faster for learning in early design stage.

6. Conclusion

In transferring students' basic knowledge of the environment and fluid dynamics from conceptual studies to practical applications, the goal of this project was to explore the opportunities and risks associated with physical and digital simulations to study the movement of sand grains along the surface of a building, when that surface was subjected to dynamic forces such as strong winds and gravity in the desert.

In environmental design education, the use of CFD software presents much of interest (Bouchahm et al. 2012). Since new generations of simulation software are easier to operate and interactively provide rapid feedback for understanding the effects of wind and other environmental forces, simulation tools will continue to be more available to architects in the coming years. As a platform for discussion and consideration of the best methods of utilizing CFD as support during the early design stages of future architects' workflow (Kaijima et al. 2013), the Breathable Wall Project underscores the great potential for the application of CFD software to improve future architects' understanding of wind phenomena. Flow Design was shown to be a proper CFD toolkit for architecture students, helping them to easily model airflow around their designs by leveraging real-time feedback.

Existing in the intersections and spaces of overlap across physical and digital simulations, the Breathable Wall Project aimed to take advantage of the arising opportunities of intertwining physical digital simulations to create an enhanced understanding of their critical dependencies.

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OPTIMIZATION IN THE ARCHITECTURAL PRACTICE

An International Survey

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Abstract. For several years great effort has been devoted to the study of Architectural Design Optimization (ADO). However, although in the recent years ADO has attracted much attention from academia, optimization methods and tools have had a limited influence on the architectural profession. The aim of the study is to reveal users' expectations from the optimization tools and define limitations preventing wide-spread adaptation of the optimization solvers in the architectural practice. The paper presents the results of the survey "Optimization in the architectural practice" conducted between December 2015 and February 2016 on 165 architectural trainees and practising architects from 34 countries. The results show that there is a need for an interactive multi-objective optimization tool, as 78% respondents declared that a multi-objective optimization is more necessary in their practice than a single objective one and 91% of them acknowledged the need for choice of promising solutions during optimization process. Finally, it has been found that daylight, structure and geometry are three top factors which architects are interested in optimizing.

Keywords. Architectural Design Optimization; Optimizaiton Techniques; Generic Solvers; Multi-criteria Decision Making.

1. Introduction

Today's challenges in the architectural industry are centred around energy saving, cost-effectiveness, and improving safety and occupant comfort. To address so many different challenges computational optimization is a must. In order to analyze and solve more and more complex design problems Artificial Intelligence is adopted to the architectural field. Evolutionary Algorithms (Rutten 2013; Vierlinger 2013), Swarm Intelligence (Cichocka et al. 2015), Artificial Neural Networks and other biologically inspired techniques are employed to support architects in discovering high-performing design solutions. Although optimization plays a vital role in the recent architectural research, optimization techniques have very barely influenced the architectural profession in contrast to the engineering design (Flager & Haymaker 2009). The time intensity and complexity of architectural design are considered as two potential reasons for the lack of the popularity of the optimization methods among architects (Wortmann et al. 2015). In ADO evaluations of the robustness of the optimization methods often are not very rigorous when compared to the mathematical optimization field. Nevertheless, optimization techniques for ADO have been being evaluated by several researchers by means of the comparisons of the different optimization techniques using quantitative benchmark problems (Wortmann & Nannicini 2016; Evins 2013; Aly & Nassar 2013; Cichocka et al. 2015). It is believed that employing the appropriate optimization method is crucial in achieving the optimal solution, especially in complex design problems (Wortmann & Nannicini 2016). However, we argue that there are other barriers that prevent practitioners from achieving optimal design solutions in their practice. The main aim of this paper is to reveal the possible improvements in the implementations of the black-box optimization algorithms in the generic solvers based on the practitioners' experience and needs. The secondary objective is to verify if there are other reasons why optimization is not commonly used in the architectural practice apart from the computational effectiveness of the employed optimization algorithms and the complexity of the architectural design problems. In this paper, we explore the users' expectations and the limitations of the optimization tools from the practitioners' point of view. The results could aid the creation of a user-friendly and robust optimization application for architects and accelerate popularization of the ADO among practitioners. Optimized real-world design problems in architecture mean comfortable, safe, cost- and energy-effective built environment. The expectations from practitioners concerning number of objectives, architectural features to be optimized and the need of education in ADO are examined and directions of the potential development of the computational optimization solvers are sketched. In the first paragraph the search strategy and criteria are presented. The second section reports on the achieved the results, which are discussed in the Discussion and Conclusion paragraphs.

2. Search Strategy and Criteria

165 architectural trainees and practitioners have participated in the survey with the professional experience ranging between 1 and 46 years (including architectural studies). This research was confidential. Neither the participants' names nor any information that would allow identification was included in the research survey.

The notes or transcript of the interview were read only by us. The interview transcripts, summaries and any recordings will be kept securely and destroyed 3 years after the research ends. The research conforms to the University's Treaty of Waitangi Statute by valuing the Tiriti o Waitangi, rangatiratanga (leadership), manaakitanga (the generous fostering of knowledge), kaitiakitanga (responsibility for, and guardianship of, knowledge), whai matauranga (intellectual curiosity), whanaungatanga (collaboration and collectiveness) and akoranga (collective responsibility for learning). Survey was conducted in the on-line form and was emailed to the target groups (architects and designers) and published in the research groups. The recipients of the link to the on-line survey form had no obligation to fill it and their participation was of voluntary nature. The participants could also quit the survey at any moment. Only submitted forms were recorded. No feedback was provided to the participants. The survey was approved by the Victoria University of Wellington Human Ethics Committee with the Ethics Approval number 223779.

3. Survey Questions and Results

The survey was composed from 13 questions: deterministic type yes/no, multiple choice and open questions.The first two questions were supposed to describe the participants based on their years of professional experience and the country where the school, university, company or organization which they were mostly associated with is based.

3.0.1. Q1 How many years have you been in the architectural practice?(open question, numerical input)

Most of the responders had the professional experience ranging between 5-10 years. The least experienced surveyee was the first year student and the most experienced one had 46 years of professional carrier.

3.0.2. Q2 In which country is the school, university, company or organization you are mostly associated with based? (open question, string input)

The responders' school, university, company or organization which they are mostly associated with are based in 34 countries with majority based in Germany, Poland, Italy and New Zealand. All countries which the participants felt professionally affiliated with and corresponding number of answers are presented below (figure 1).

3.0.3. Q3 Do you use any parametric design software packages in your practice? e.g. Grasshopper3D, Dynamo for Autodesk Revit, GenerativeComponents (single choice: yes or no)

- *yes* (83.0%)
- *no* (17.0%)

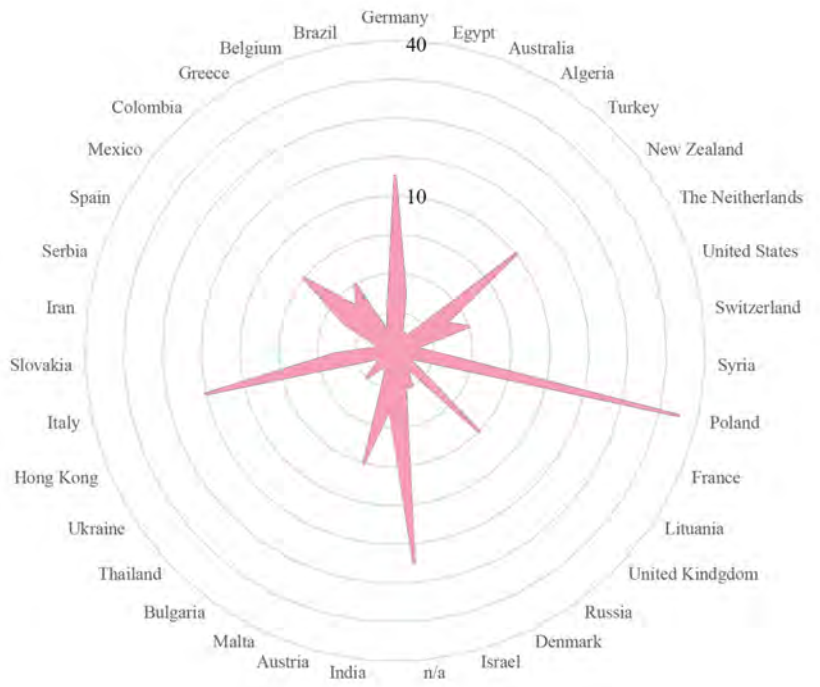


Figure 1. The countries which respondents associate their professional carrier with. n/a means that the responder did not indicate any country.

If *yes* was selected in the Q3 question the surveyee was asked to select the software that she or he used most often with only one choice possible (single choice).

- *Dynamo for Autodesk Revit* (6.6%)
- *Grasshopper3D for Rhinoceros3D* (89.9%)
- *GenerativeComponents for Microstation* (0.0%)
- *Digital Project* (0.7%)
- *other* (2.9%)

83% of the survey's participants use parametric design software packages e.g. Grasshopper3D, Dynamo for Autodesk Revit, GenerativeComponents in their practice. As presented in the figure 2, Grasshopper3D for Rhinoseros3D is the most popular design platform. This result confirms that Grasshopper3D has gained most popularity in academia and among professionals, leaving the other parametric software applications behind (Vierlinger 2013; Martyn 2009).

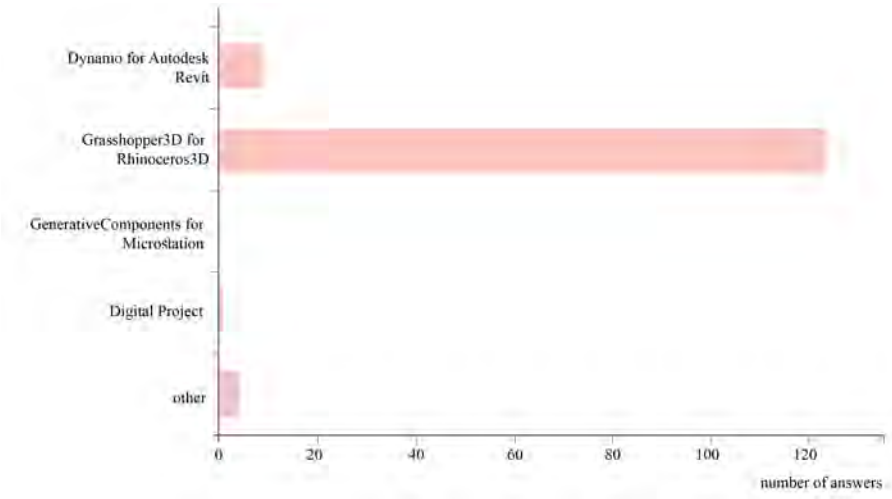


Figure 2. The popularity of the parametric modelling tools among surveyees.

3.0.4. Q4 Do you use any scripting tools in your design practice?(single choice: yes or no)

- *yes* (57.6%)
- *no* (42.4%)

If *yes* was selected in the Q4 question the surveyee was asked to select the scripting or programming languages that she or he used from the list below with multiple choice possible.

- *Processing* (26.2%)
- *RhinoScript in Rhinoceros3D* (13.5%)
- *C sharp in Grasshopper3D* (12.7%)
- *Visual Basic in Grasshopper3D* (11.1%)
- *Python in Grasshopper3D* (28.6%)
- *Python Script in Blender* (0.7%)
- *MEL in Autodesk Maya* (3.2%)
- *other* (4.0%)

57.6% of the surveyed trainees and partitioning architects declared to use scripting tools in their professional activities. Python for Grasshopper3D and Processing reached the greatest popularity among following programming languages: Processing, Rhinoscript in Rhinoceros3D, Visual Basic, C sharp and Python in Grasshopper3D, Python Script in Blender and MEL in Autodesk Maya. Rhinoscript in Rhinoceros3D and C sharp in Grasshopper3D were selected almost the same number of times and they are second commonly used programming languages in design practice. 37% of respondents using scripting tools in his/her practice declared to use more than one programming language (35 surveyees).

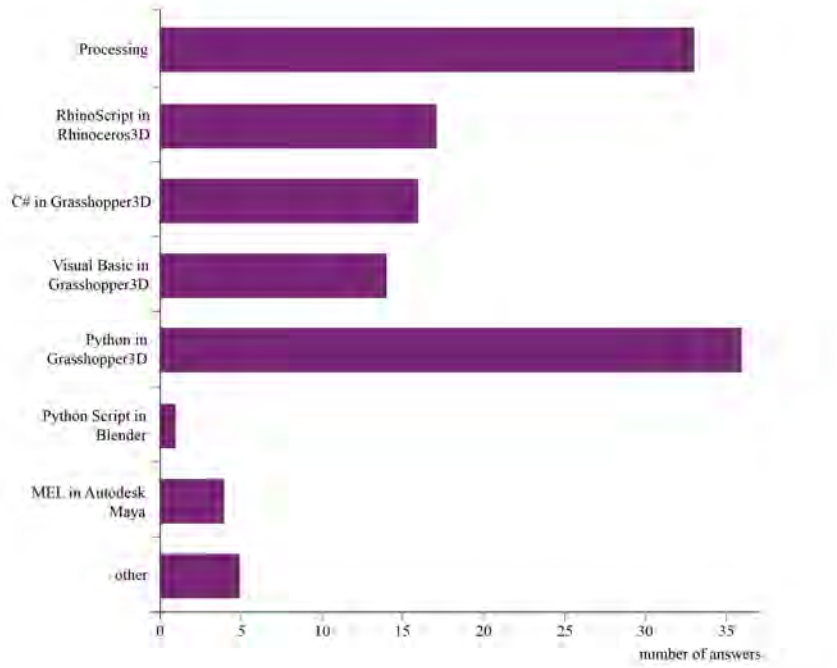


Figure 3. The scripting or programming languages selected as used by architectural trainees and practitioners in their practice.

3.0.5. Q5 Would you like to optimize your designs without the need to produce scripts?(single choice: yes or no)

- *Yes* (86.8%)
- *No* (13.2%)

87% architectural trainees and practitioners would like to optimize designs without the need to produce scripts.

3.0.6. Q6 Would you commonly optimize one feature of your design or many features at once?(single choice)

- *one feature (single objective optimization)* (21.7%)
- *many features (multi-objective optimization)* (78.3%)

78.3% of respondees have stated that most commonly they would optimize many design features at once.

3.0.7. Q7 Which aspects of your design would you like to optimize?(multiple choice)

- *daylight availability*
- *circulation*
- *layouts*
- *views*
- *structure*
- *general shape for building code/regulations*
- *other*

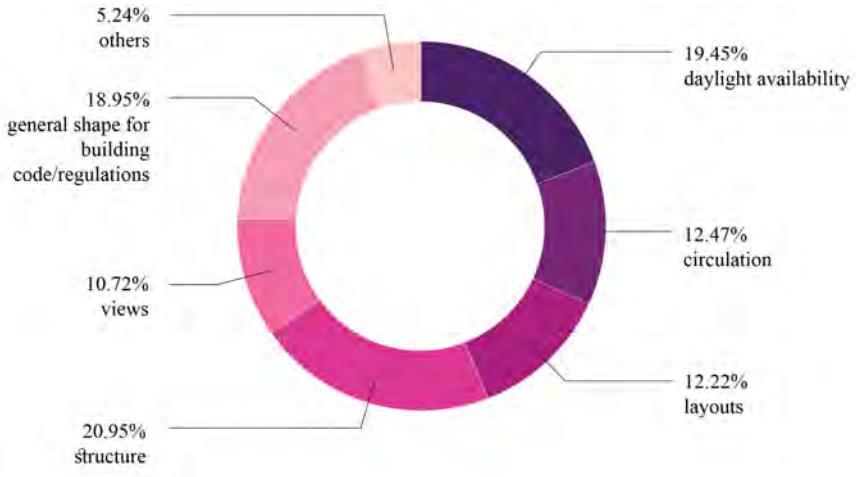


Figure 4. Architectural features selected by respondents to be optimized.

3.0.8. Q8 In the optimization process would you prefer to: (single choice)

- *run it with default settings and do not spend much time on tuning the settings* (15.2%)
- *spend some time to tune a few settings provided I understand how they influence the accuracy and time of the optimization process* (30.5%)
- *have the possibility of changing every parameter in the optimizer in order to have full control over the process* (54.3%)

3.0.9. Q9 Would you like to influence outcomes by choosing promising designs during this optimization? (single choice: yes or no)

- *Yes* 90.7%
- *No* 9.3%

91% surveyed architects would like to influence outcomes by choosing promising designs during optimization process.

3.0.10. Q10 As an optimization outcome would you prefer to get: (single choice)

- *one best design solution* (17.8%)
- *a few high-quality solutions* (82.2%)

If *yes* was selected in the Q10 question the surveyee was asked to specify how many solutions she or he would like to compare. 70% of the survey participants would like to have a choice between 3 and 5 optimized design options, and 17% of respondees would prefer the choice between 6 and 10. It has to be mentioned here, that most probably the resposnders expect different solutions to be compared. The diversity of the optimized solutions directly relies on the number of objectives and the size of the domain of the given parameters. Summing up, it is evident that the vast majority of the surveyed architects would like to have a choice between 3 and 10 optimized design options.

3.0.11. Q11 In the early design stage, how long could you wait for the solution or the catalogue of solutions from the optimization process? (single choice)

- *up to 5 minutes* (29.6%)
- *up to 1 hour* (36.0%)
- *up to 1 day* (31.2%)
- *up to 1 week* (3.2%)

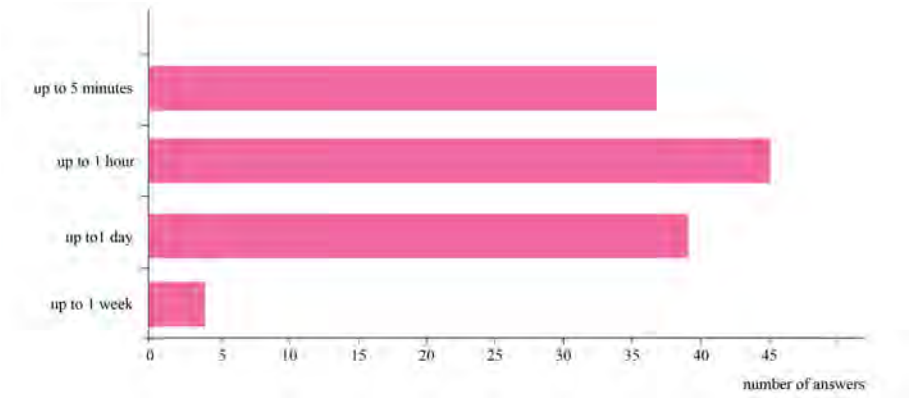


Figure 5. The maximum amount of time that participant would like to wait for the answer from the optimization process.

Architectural designers are not unanimous in the potential time cost which they could pay for achieving optimized design solution(s). In general optimization processes that could take more than one day would be avoided in practice.

3.0.12. Q12 Would you like to understand why an optimizer selected the presented solution(s) over other alternatives? (single choice: yes or no)

- *Yes* 92.8%

- *No* 7.2%

92.8% of the architectural designers would like to understand why the solver selects the particular solution over alternatives.

3.0.13. Q13 Could you describe any architectural design problem you have ever come across, that you wanted to solve or optimize with computational optimization tools? Describe the aim that you wanted to achieve, the constraints of the problem and how you solved the problem.

This question revealed some of the real-world problems that have been already encountered in the architectural practice. Respondents among others enumerated following problems: multi-criteria problems in designing shading devices (membranes or louvers) aiming at minimization of the material use, with solar radiation analysis and structural and manufacturing constraints; rationalization of paneling systems of the complex surfaces aiming at planarization of elements and adjusting them to the fabrication constraints; structural form-finding with multiple factors determining form, optimization of the shapes of trusses and cross sections of structural elements; layout optimization and block programming based on the user defined adjacencies and user-friendliness; managing thermal and electrical capacity in accordance to building shape and occupancy. Participants also mentioned topics that would be difficult to solve with numerical optimization techniques like material aging or predicting the future.

4. Discussion

The results of the survey confirmed the previous researchers' statements (Martyn 2009; Vierlinger 2013) that Grasshopper3D for Rhinoceros3D is the most often parametric software selected by architects for use. *Dynamo for Autodesk Revit* has been indicated as the second most popular visual programming design platform.The results obtained from the survey have indicated directions of the development of computational optimization methods that would fit to the needs of practitioners. Nevertheless, it stays unclear if the computational expensiveness is the crucial factor that prevents architects from using optimization tools. It has also to be underlined that only people interested in the latest design techniques and optimization in architectural design responded to the survey. The group of surveyors included mostly young practitioners up to 5 years after graduation, therefore brought research questions stay unanswered from the older and more experienced generation of architects.

5. Conclusion

From the research that has been undertaken, it can be concluded, that multi-objective optimization techniques/tools are more necessary in the architectural practice than single objective ones. Moreover, it has been demonstrated that majority of practising architects (93%) would like to understand the underlying optimization procedures and 54% would prefer to have full control over optimization process, thus intuitive and easy to-understand optimization algorithm would be more suitable in the architectural practice. Furthermore, the interactive optimiza-

tion methods and 'human in the loop' approach seem the most appropriate, as almost all of surveyees (91%) would like to select promising designs during the optimization process. Finally, this paper has clearly shown that daylight, structure and geometry are the three top features that architects are interested in optimizing.The obtained results might help in improving technological, implementational and educational aspects of optimization processes in the building industry. Consequently, robust optimization processes could significantly reduce carbon-footprint, reduce the material use and increase the energy-efficiency of the future architecture.

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OPTIMIZATION OF WINDOW-WALL-RATIO USING BIM-BASED ENERGY SIMULATION

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Abstract. In this research, sensitivity analysis is applied to investigate the impact from U-values of walls, U-value of windows, and the window-to-wall ratio. The purpose is to find the co-relationship between those parameters with the building energy performance, including embedded energy in materials and operational energy during the lifecycle. Building Information Modeling (BIM) is used as a platform to obtain the material quantities and carry on energy simulation. A case study is applied for a manufactory plant in Suzhou, China. By applying both local sensitivity analysis and global sensitivity analysis, it is found that thermal properties of walls have insignificant impact on Operational Energy to Embodied Energy (OE-EE) relationship of Window-Wall-Ratio (WWR) whereas changing thermal properties of windows affects the OE-EE relationship behaviour of WWR. Lowering U-value of windows brings positive impact to the OE-EE relationship of WWR, and vice versa. Therefore, suggestions are made as reducing/increasing U-value of windows while increasing/decreasing the WWR of building.

Keywords. Building Informaion Modeling; Window-Wall-Ratio; energy simulation.

1. Introduction

According to the European Union report, 40% of the total energy was consumed in the building sector. Over 80% of energy was consumed during building's operational stage. In addition, energy embodied in construction materials is also huge, e.g., producing cement is an energy-intensive process. Therefore, a proper building design help reduce building's environmental impact during its lifecycle. Architectural daylighting design is at the heart of sustainable building design. Daylighting, which is the use of natural light in a building, plays a significant role in reducing the amount of artificial lighting that is needed to light the interior of a building. When properly designed and effectively integrated with the electric lighting system, daylighting can offer significant energy savings by offsetting a portion of the electric lighting load. Larger window areas are preferred to allow

more natural light into the building. However, larger value of window-wall-ratio (WWR) may cause more energy consumption to compensate heat loss through the building envelope during operational stage. Therefore, finding an optimal WWR to meet both natural lighting requirements and energy saving is essential. In this study, main design parameters that affect the building performance are selected, which include the U-value of walls, U-value of windows, and window-wall ratio, etc. Building Information Modelling (BIM) is used as a platform to enable energy simulation, material quantity take-off, and data integration. Simulation of energy consumption is run for different scenarios in terms of energy consumption during operation stage. Energy embodied in typical construction materials are calculated for each scenario and combined with the building energy consumption results from the energy simulation. Sensitivity analysis (SA) is applied to find the relationship between changing the parameter values and the energy performance of the building and impact of the WWR on building performance is identified.

2. Methodology

First of all, the base model of a building was created by BIM and the properties of building were defined in the model. Next, the energy baselines were calculated upon the base model, include operational energy (OE) and embodied energy (EE). BIM provides a quick access of materiel quantity so as to calculate the EE. The energy analysis was run iteratively by varying one or more design parameters while all other parameters were set to be constant. In this research, the output results of interest is the energy used in the building during its lifetime operational stage, i.e. operational energy (OE), assuming the lifetime of building is 50 years. With respect to each design parameter changes, the information of energy used in building were obtained from the simulation output result and the EE of building envelope was calculated based on the quantity and energy coefficient of material. Lastly, the correlation degree between OE and EE for each envelope element respect to the design parameter was measured and compared to identify the most influential design parameter which is the one that the output results have highest degree of variation with respect to its change. A sensitivity indicator was chosen to represent the sensitivity results, which provide the importance of design parameter to EE and OE of buildings.

Table 1. Typical Range and Recommended Maximum Value.

Design parameters		Typical range	GB50189-2015 recommended maximum value
U-value ($W/m^2 K$)	Wall	0.37 – 1.95	0.5
	Window	1.70 – 6.00	3.5
	Roof	0.18 – 3.00	0.8
WWR		0.10 – 1.00	-

To perform SA, the design parameters were varied in the model from baseline value within certain range and interval to create different scenarios, while other design parameters were fixed to its base model value. Table 1 tabulates the typical range and recommended maximum value by GB50189-2015 for the design

parameters (Dowd & Mourshed 2015; Harwell 2016; Hussain 2015; Ioannou & Itard 2015). According to literature, the U-value of walls and roof are affected by thermal mass and insulation whereas for windows, the glazing type and number of layer are the impact factors to consider. The typical WWR is range from 0.10 - 1.00, as shown in table 1. It is defined as the ratio of window area (Awd) to wall area (Aw). The target WWR can be achieved by changing the size and number of windows. In this research, the latter was used as the approach to vary WWR. Depending on glazing type and the number of glazing layer, the U-value of windows was modified by varying the thickness of glass plane, which is the traditional variable of windows (Lam & Hui 1996). According to literature, for glazing with two or more layers, the ratio of air space between glass plane and thickness of glass was generally to be 2:1. Therefore, the air space was assumed to be twofold of the glass thickness. In this research, double layered window is considered. A sensitivity indicator was selected to evaluate the sensitivity of design parameters on OE. Different methods for sensitivity analysis, both local and global, are available, such as sensitivity coefficient (SC), standardized regression coefficient (SRC), etc. In this research, SC and SRC were selected as local and global sensitivity indicator respectively to measure the sensitivity of each design parameter on OE of building and its energy-efficiency. Due to space limit, only the result of SC is presented in this paper.

3. Case Study

The case study is done based on a 3-storey industrial plant under construction in Suzhou.

3.1. BASE MODEL DESCRIPTION

The 3D model of a manufacturing building was created by using Autodesk Revit. While the building energy analysis was performed by Energy Analysis (EA) option in Revit. It is an add-in tool for Autodesk Revit that links the design feature of the model to analysis feature of Green Building Studio (GBS). The energy simulation performed in GBS uses DOE2 simulation program to run building model simulation with the purpose of producing sustainable and energy efficiency design in the earlier stage (Mohammad & Shea 2013). This program has been used widely to perform energy modelling and its accuracy and consistency have been validated. However, DOE2 has limitation in dealing with complicated model that consists of large number of data required to handle and analyze (Ochoa et al. 2012). Therefore, to guarantee robustness and consistency, the model was simplified to consider only first floor of case study building for energy simulation. The details of case study building are given in table 2. Figure 1 shows the simplified first-storey model that was used for energy simulation in the research.

Table 2. Description of simplified case study building.

	Description
Floor area	1916 m^2
Height	6 m
Wall area	1128 m^2
Window area	202.46 m^2
Roof area	2402 m^2
WWR	0.22
External walls	Autoclave aerated concrete
Roof	Lightweight concrete
Windows	Double clear glazing filled with air

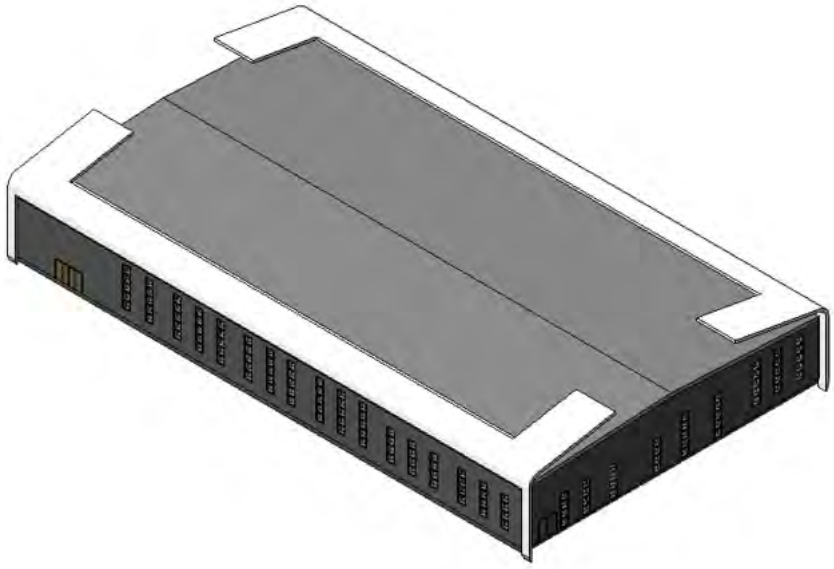


Figure 1. Simplified base model.

The design parameters of interest were varied by increasing and decreasing from base model value within certain range and interval as shown in table 3. As the target U-value of element is achieved by varying its thickness, the corresponding thickness of elements respect to the design parameters of model is calculated.

Table 3. Four design parameters.

Design parameters		Base model value[1]	Range	Interval
U-value (W/m² K)	Wall	0.50	0.35 – 0.65	0.05
	Window	3.00	2.10 – 3.90	0.30
WWR		0.22	0.00 – 0.34	0.04

As shown in figure 2, it was found that the U-value of walls and windows have strong positive linear relationship with the OE of building. These findings are in agreed with the study of Ioannou & Itard (2015) and Yu et al. (2013), which the higher the U-value of building envelope elements, the more energy is required to maintain the operation of building (Scheer 2013; Yu et al. 2013). Results show that the U-value of wall has the higher gradient slope value respect to OE of building. Therefore, to reduce building energy consumption, lowering the U-value of wall to improve the thermal properties of building envelope can be taken as a priority.

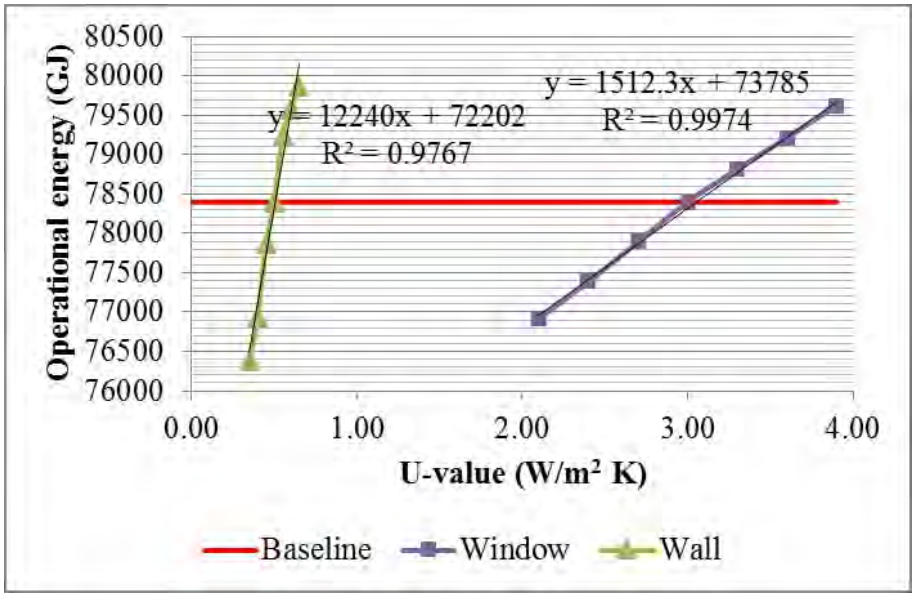


Figure 2. The impact of U-values of wall and window on OE of building.

Figure 3 shows the impact of increasing WWR on OE. It is a U-shaped curve with optimum lying at WWR of 14%. The variation of OE with WWR changes is attributed to the change in the area of windows and walls affects the thermal loads of buildings, such as solar heat gain, heat conduction across envelope element and internal heat gain, and subsequently impact the heating and cooling required by HVAC to maintain thermal comfort within buildings.

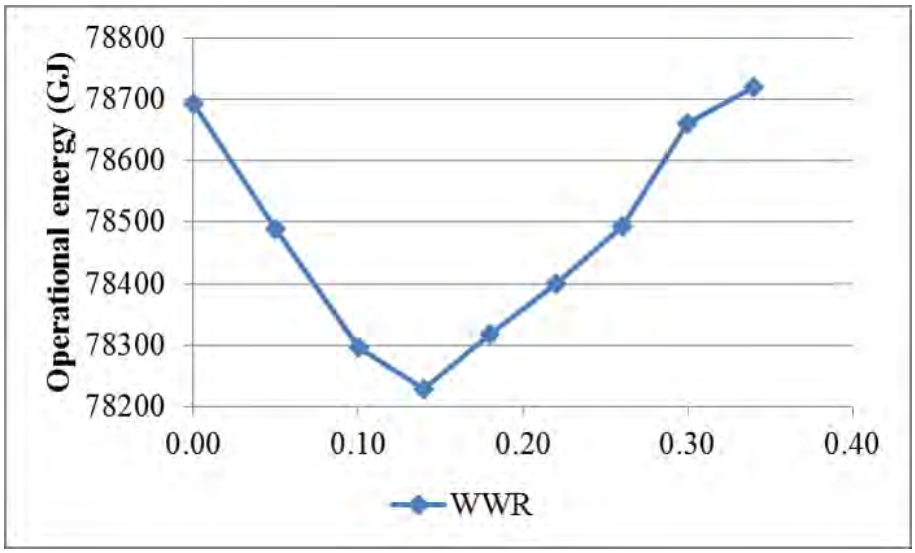


Figure 3. The impact of WWR on OE of building.

However, it was observed that the OE-EE relationship of WWR in LSA is neither linear nor monotonic when U-value of walls and windows were kept to its base value, i.e. the OE of building is inconsistent when EE of building envelope varied with WWR, contrasting with other design parameters. This is due to the thermal load of building changes inconsistently when WWR is varying. Besides, wall and window materials have distinct amount of EE, therefore the variation of WWR, which alters the area of wall and window in building envelope, would change the EE of building envelope as well. This brings out the need for GSA in order to explore more thoroughly the relationship between WWR and EE of building envelope, subsequently the impact on OE of building with considering the interactions among design parameters and offer more reliable energy saving practices.

In GSA analysis, the sensitivity of WWR on OE of building together when changing U-value of walls and windows simultaneously was investigated in 62 scenarios. As shown in figure 4, variation of OE with WWR in respect to change in U-value of walls or U-value of windows from its base value, while other parameters were kept constant. It was observed that with the increase of WWR, keeping U-value of windows to base value and changing U-value of walls from base value merely influences the amount of OE which the higher U-value, more OE is required (Line 1 and Line 5 in figure 4). This is due to change in heat conduction across walls associated with the variation of U-value and these practices would not change the relationship behaviour between OE and WWR as in figure 3, i.e. OE of building remains inconsistent with the variation of WWR. On the other hand, changing U-value of windows from base value affects trend behaviour of relationship between OE and WWR. For the scenarios of lowering U-value of windows and keeping U-value of walls to base value, instead of having inconsistent rela-

tionship between WWR and OE, the OE of building is decreased with increasing WWR (Line 4 in figure 4). In contrast, the OE in the scenario with higher U-value of windows is in opposite trend: it is increased with increasing WWR (Line 2 in figure 4). In summary, the findings from EE based LSA and GSA of OE with respect to the variation of WWR, U-value of windows and U-value of walls are summarized in table 4 as follows:

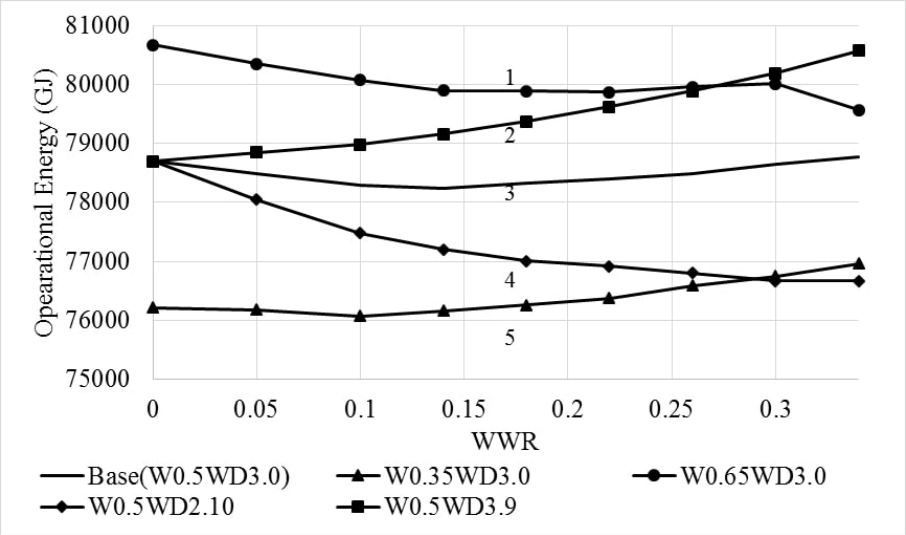


Figure 4. The variation of OE with WWR with respect to change in U-value of walls or U-value of windows.

Table 4. Summary of Findings.

No.	Findings
1	OE of building is more sensitive to the variation of EE due to U-value of windows changes and less sensitive to the variation of EE due to U-value of walls changes.
2	Thermal properties of walls have insignificant impact on OE-EE relationship of WWR whereas changing thermal properties of windows affects the OE-EE relationship behaviour of WWR.
3	Lowering U-value of windows brings positive impact to the OE-EE relationship of WWR.
4	Increasing U-value of windows brings negative impact to the OE-EE relationship of WWR.

Based on these findings, it was concluded that targeting on thermal properties of windows when varying WWR brings noticeable impact to both EE of building envelope and OE of building. Therefore, the suggestions for designer in selecting efficient building envelope designs are tabulated in table 5 as follows:

Table 5. Summary of Suggestions.

No.	Suggestions
1	Minimize U-value of windows and maximize U-value of walls during design stage
2	Minimize U-value of windows when consider to increase the WWR of building.
3	Maximize U-value of windows when consider to decrease the WWR of building.

4. Conclusions

Both LSA and GSA methods were used in this research to quantify the impact of input variation on output results. In LSA, the considered design parameters are U-value of walls, U-value of windows, and WWR. Sensitivity coefficient was selected as sensitivity indicator for LSA. Based on the proposed methodology, it was found that the OE-EE relationship of windows has steeper gradient slope. Therefore, among the element envelopes considered in this research, OE of building is most sensitive to the variation of EE due to U-value of windows changes. Therefore, targeting on thermal properties of windows during optimization process would bring the most benefit in term of LCE saving.

GSA focused on the OE-EE relationship of WWR by changing the U-value of walls and U-value of windows together. The findings from GSA are that the thermal properties of walls have insignificant impact on OE-EE relationship of WWR and lowering U-value of windows is the most influential energy-efficient practice that brings positive impact to the overall LCE of building. Therefore, when varying WWR during design stage, targeting on thermal properties of windows would bring noticeable impact to both EE of building envelope and OE of building and help to develop an energy-efficient design scheme that can reduce the overall LCE of building.

It was found that the scenario with the highest OE reduction or EE reduction is neither optimized nor energy-efficient from the perspective of LCE. Nevertheless, the top 5 energy-efficient scenarios are belonging to those with lower U-value of windows, which are in agreed with the findings from GSA, therefore this indicates that the findings from the proposed methodology in this research are reliable.

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EMPOWERING URBAN DESIGN PROTOTYPING

A Case Study in Cape Town with Interactive Computational Synthesis Methods

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Abstract. Although Cape Town city in South Africa is generally regarded as the most stable and prosperous city in the region, there are still approximately 7.5 million people living in informal settlements and about 2.5 million housing units are needed. This motivates the so-called Empower Shack project, aiming to develop upgrading strategies for these informal settlements. To facilitate the fulfillment of this project, urban design prototyping tools are researched and developed with the capabilities for fast urban design synthesis. In this paper we present a computational method for fast interactive synthesis of urban planning prototypes. For the generation of mock-up urban layouts, one hierarchical slicing structure, namely, the slicing tree is introduced to abstractly represent the parcels, as an extension of the existing generative method for street network. It has been proved that our methods can interactively assist the urban planning process in practice. However, the slicing tree data structure has several limitations that hinder the further improvement of the generated urban layouts. In the future, the development of a new data structure is required to fulfill urban synthesis for urban layout generation with Evolutionary Multi-objective Optimization methods and evaluation strategies should be developed to verify the generated results.

1. Introduction

Modern urban design is characterized by increasing complexities and dynamics. However, traditional urban design methods still rely heavily on the static and sectoral approaches, which cannot fully fulfill such complex and dynamic requirements. At the same time, from modelling to manufacturing, computers are playing an increasingly important role in the design process. Many phases in design once

carried out by hand are nowadays automated (Bolognini et al. 2011). The automation of urban design enables the fast exploration of different design possibilities so that the designers could have a comprehensive overview and understanding of different design choices through their interaction with the computing tool. This method is what we call Urban Design Prototyping (UDP), which employs computational synthesis methods, aiming at facilitating designers' task through the automated generation of optimal urban design solutions.

Urban Design Prototyping is deeply rooted to the so-called Virtual Prototyping (VP) which has been widely studied and implemented for engineering designs (Reinhardt et al. 1993; Malik et al. 2006; and Bringmann et al. 2015). From the definition of Song et al. (1999), VP refers to "the process of simulating the user, the product, and their combined (physical) interaction in software through the different stages of product design, and the quantitative performance analysis of the product", which is emphasized on the interaction between human and product, and the role of VP in the design process (Wang 2002). As a subset of Virtual Prototyping, Urban Design Prototyping adapts this philosophy to the context of urban design, where the footstones are the interaction between urban designers and urban layout, and the functions of the prototyping tools for analysis and prediction. Inherited from VP, UDP also has the advantage of reducing time, saving costs, and increasing quality (Rix et al. 2016). More specifically speaking, it reduces the time for urban designers to explore different possibilities of mock-up urban layouts; it saves the costs of manpower and fortifies the quality of the design solutions by testing out different possibilities.

The present research evolves within the context of the Empower Shack project (Urban ThinkTank 2016), taking place in the Cape Town city in South Africa where there are still approximately 7.5 million people living in informal settlements and about 2.5 million housing units are needed. The Empower Shack project aims to develop upgrading strategies for these informal settlements. Our research is alight to meet one principle of this project, the "scalable methodology" principle which is to enhance the design process with new digital planning tools and evaluation framework to ensure the scalability and relocability. To fulfill that, our proposal is to develop one portable UDP tool that could be fast adaptive to changes of the requirements from urban designers and stakeholders. Besides, our tool is "designer-centered" with two major characteristics that should be highlighted. The first one is the capability of interaction between the designers and the program whereas the second one the capability of generating urban layouts based on parameters popularly used in urban design rather than in computer science. They are important because in reality, computers in many cases are not as creative as the human designers. The interaction helps improving the design and parameters in the "right language" help urban designers to specify their needs naturally. For the interaction, it is realized with an existing software platform, Rhino together with its add-on Grasshopper, which is relatively familiar to urban designers. For the parameters, they are determined through discussions with urban designers and stakeholders of the project. In this way, with this paper, we present a computational method for fast interactive synthesis of urban design prototypes by concentrating on i) the description of the methods for the generation of urban fabric and ii) the

presentation of a case study.

The remainder of the paper is composed of four sections: methods, case study, results and discussion, and conclusion and future work. In the methods section, the data structure and algorithm are explained for the representation and the generation of the three basic urban elements, namely, street network, parcels and buildings. In the case study section, specific requirements of the Empower Shack project concerning our tools are introduced. In the results and discussion section, the generated urban layouts are presented and current problems and limitations, received from the stakeholders concerning the data structure are discussed. In the conclusion and future work section, the paper is summarized and concluded, and research and development of the tool in next phase are proposed.

2. Methods

In our study, urban features have been simplified to four basic elements, namely, streets, blocks, parcels and buildings. For the representation of the street network, the instruction tree (Koenig et al. 2013) is employed, which has been implemented and tested in earlier versions of CPlan (Koenig 2015) and will not be introduced in detail in this paper. For blocks, they are nothing else but enclosed street segments. Buildings, on another hand, are independent on the generation of the street network and blocks because they are just polygons placed inside the parcels. Obviously, we lack one data representation of the parcels as the bridging feature between street network (blocks) and buildings. Therefore, in this section, the data structure for the parcels are majorly introduced.

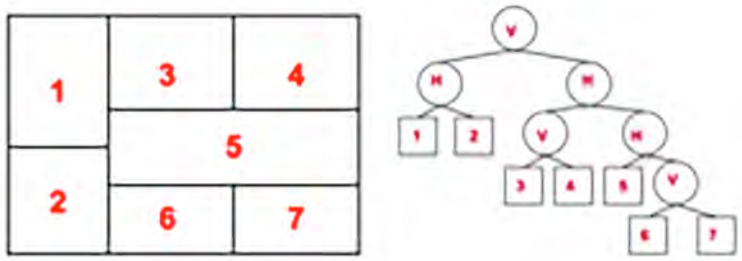


Figure 1. The slicing tree structure. On the left side, it is the geometric representation of the sliced parcels. On the right side, it is the tree representation of the sliced parcels. 'V' indicates vertical slicing whereas 'H' horizontal. Indices of the parcels on the left are corresponding to the ones on the right.

For the representation of the parcels, the subdivision method with slicing tree data structure is employed due to its efficiency to be created and searched (Koenig & Knecht. 2014), for example, for nearest neighbor queries. The data structure is relatively straight-forward to understand as can be seen in figure 1. On the left side, it is the geometric representation of the parcels sliced within a block. On the right-hand side, it is the tree representation of the parcels where the rules to slice are encoded in the nodes. The whole slicing process is depicted step by step as in figure

2. This is a recursive process and the program stops slicing after reaching certain threshold. From the paper of Koenig & Knecht. (2014), the stopping criteria is the specified threshold for the area of the individual leaf (in their cases, rooms for floorplan). In this case, the width of the parcel is more important according to the stakeholders. Therefore, the stopping criteria is the threshold for the width of the parcels, which can be interpreted as the minimum width of the parcels.

In the urban layout generation process, the slicing is only performed on the "street" to ensure that all the parcels are along the streets. One example is as in figure 1, parcel 5 is longer than the others but not sliced further because there is only one edge on the street, whose length is not long enough for further slicing. In reality, the shapes of the blocks are usually more complicated than those in figure 1 and figure 2 and the slicing might not work consistently. To deal with this problem, Koenig & Knecht (2014) sliced vertically or horizontally on the rectangular bounding box of the space as in the left depiction of figure 3. However, it also generates parcels with irregular shapes, which are not suitable for urban design. Instead, in our implementation, the minimum bounding box is calculated and slicing is performed on the minimum bounding box as can be seen in the right depiction of figure 3. Moreover, to keep the slicing perpendicular to the street segment, the shapes are rotated before being sliced as can be seen in figure 4. After being sliced, the shapes are rotated back to their original positions.

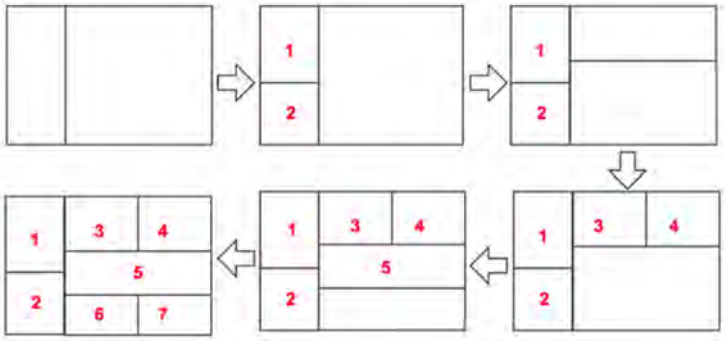


Figure 2. The slicing process. Indices in red are the parcel indices corresponding to the ones in figure 1.

For the development of the components in Grasshopper, each step in the generative process is implemented as one component, including the generation of street network, extracting blocks from the street network, slicing the blocks into parcels, and placing buildings in the parcels as can be seen in figure 5. Grasshopper is currently used as an interface for the CPlan framework, given its popularity among urban designers and architects and the existing abundant and versatile add-ons. This tool is adapted to the case study of the Empower Shack project which will be introduced in the following section.

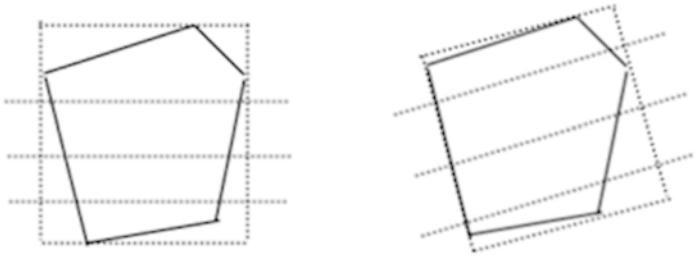


Figure 3. Slicing on the boundary box of irregular shapes. On the left, the slicing is performed on the normal bounding box whereas on the right, the slicing is on the minimum bounding box.

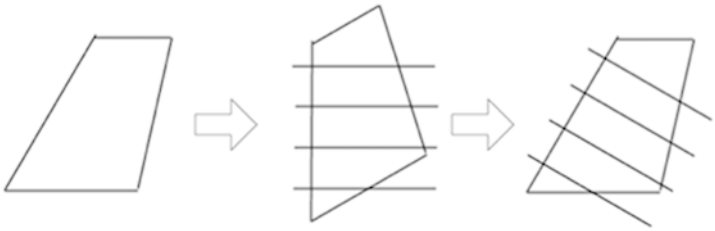


Figure 4. Slicing on the rotated shape so that the slicing lines are always perpendicular to the longest street.

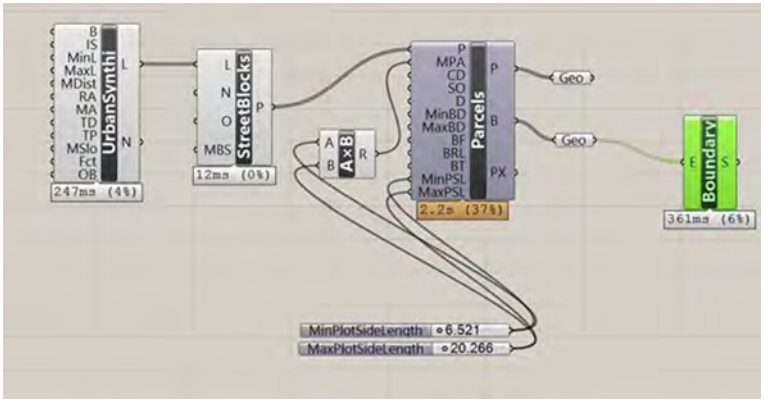


Figure 5. The Grasshopper components for street network, street blocks, parcels and buildings.

3. Case Study

Our case study was conducted within the Empower Shack project, which is led by the Urban ThinkTank (UTT) group (2016). One important aim of the project was to develop a layout of streets and parcels that would allow a maximum density for the two-story houses, which densify an area that was used for informal one story buildings. The study area is Enkanini in Cape Town City, South Africa as can be seen in figure 6. Our methods and tools provide practical avenues for the planners to obtain prototyping suggestions in a fast and interactive way. Moreover, the generated urban fabric could be used as an input for various simulations measuring its performance concerning, for example, security, fire protection, and traffic potential.



Figure 6. The study area selected from the Empower Shack project.

The requirements from UTT and the stakeholders were defined as follows: the tool should be able to fit as many regular shaped (close to rectangles but not necessarily to be) parcels as possible in the study area; the streets should be possible to be moved manually so that the generation of the parcels could adapt automatically; the dimensions of the parcels should be able to be specified and generated precisely; boundaries can be specified and distinguished from street segments; and the Grasshopper interface can be connected to a web interface. With our method, we were able to fulfill these requirements and generate layouts as in figure 7. For the generation of such layouts, the user only needs to specify the dimensions of the individual parcel (width and length), which is simple for the urban designers to use. Moreover, further spatial analysis can be performed based on the generated urban layouts and displayed on web, as the example in figure 8 shows.



Figure 7. The urban layout for the sliced parcels and buildings within the parcels.

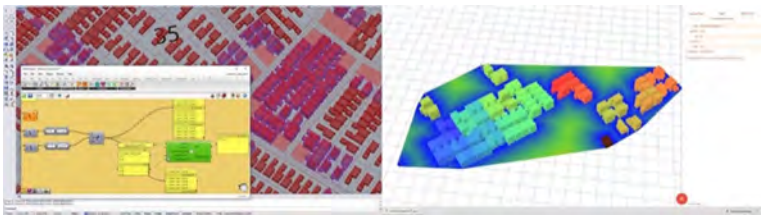


Figure 8. Different variations for synthesized neighbourhoods in Cape Town using a parametric modelling approach. The colours in the layouts show a distance analysis. In this case the area that can be seen from one location is encoded by the colours (blue nearest distance area, green maximum distance). The results can be visualised in a web browser.

4. Discussion and Future Work

From the results shown in the case study, the requirements from the Empower Shack project can be fulfilled with our tool. The urban layouts can be automatically generated based on simple parameters, namely, width and length of the individual parcel, specified by the users. Moreover, the urban designers can interactively revise the urban layout by moving the street segments to achieve satisfying results.

However, there are also limitations of the method. During the study and implementation, three major issues were discovered and partly solved. The first issue was the limitation of the slicing tree data structure for the generation of the parcels. Given the top-down recursive nature of the structure, the generated parcels cannot be guaranteed to be with the precise width and length specified by the users. The slicing stops when the threshold was reached and thus parcels with wider width were generated occasionally. This problem was solved by pre-partitioning the blocks. A slicing tree was still used for the generation of the parcels. However, instead of slicing an irregular block at once, the block was firstly partitioned into several small blocks with regular shapes. The number of the polygons after the partition can be calculated by solving equation 1 below, which is the number of "a" that is equal 1. For clarification, one example is illustrated in figure 9. As can be seen from the figure, the length of the longest edge is 20 m and the width of the parcel is specified as 2 m. To get precise solutions, the edge is firstly partitioned

into two polygons. After the partition, there are two slicing trees that can be used for slicing the region: one is with depth of 3, whereas the other one with depth of 1. However, there are two problems with respect to this method. The first one is that the parcels can only have integer width. The second problem is that it cannot be used to specify precisely the length of the parcel.

$$\lfloor L \rfloor = \sum_{i=0}^{n} a \cdot \lfloor W + 1 \rfloor \cdot 2^n; n = \lfloor \log_2 L \rfloor; a = 0 \quad \text{or} \quad 1 \tag{1}$$

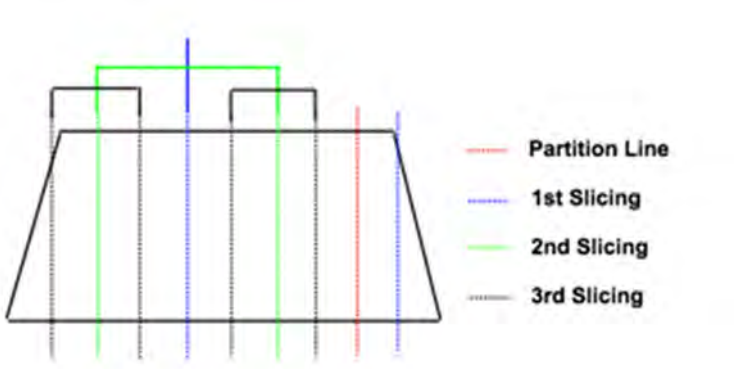


Figure 9. The adapted slicing tree structure. The slicing is based on the bottom edge (longest) with a length of 20 meters. The width of the parcel is specified as 2 meters.

To deal with the above-mentioned issue, a nested method was introduced. In Grasshopper, the blocks were first partitioned into smaller blocks with defined width and then partitioned again into parcels. Although the above-mentioned method could be used to solve the problem, it shows that in reality, the top-down hierarchical slicing structure is not the ideal structure for urban design, especially that it can only be used to fulfill global parameters rather than local ones.

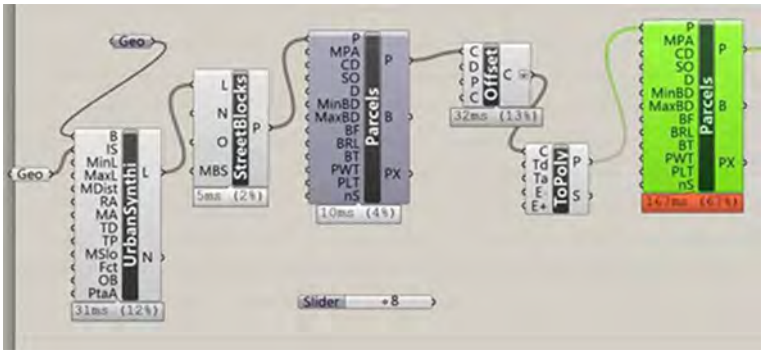


Figure 10. An illustration of the nested method. Blocks are firstly partitioned into smaller ones with the slicing tree and then partitioned into parcels.

Another issue is about the growth of the street network. Given the hierarchical nature of these urban features, the generated solution of the parcels is very much dependent on the generated result of the street network. This leads to a lot of manual revision during the interaction process which spoils the user experience. The ideal solution will be a new data representation for the parcel that could have two characteristics. The first one is that it can take the local specifications into account, say, parameters for individual parcels. The second one is that it can grow with the street network and have mutual influence with each other so that the generated street network can better fit the parcels.

For urban synthesis, Evolutionary Multi-objective Optimization has been proved to be effective (Koenig et al. 2014). However, with the current data structure, the optimization can only be performed hierarchically one urban feature after another, which cannot guarantee the Pareto efficiency for all (Kanbur 2005). A new data structure is required to abstract the geometric representation of the parcels into genotypes so that all urban features can be optimized all together. Moreover, a backcasting strategy (Koenig & Schmitt 2016) can be employed for the next generation tool of computational urban design.

5. Conclusion

From our case study, it has been proved that our methods can efficiently and effectively assist the urban planning process in practice. Planners can benefit from the interactive fast prototyping which saves a lot of manual work and improves the planning efficiency. It has been found that interaction between urban designers and computer can not only save urban designers' troubles, but also reveal the problems concerning the computer programs themselves, which is inspiring for the computational scientists and software developers.

However, it has also been found in practice, that the data representation for the parcels has its own limitations to fully fulfill the needs of urban designers. In the Empower Shack project, the problem lies in the ability to precisely represent the parcels with specified dimensions. Although remedies have been proposed and implemented as intermediate solutions, a new data structure is required to solve the problem fundamentally.

In future, abstract representations as inputs for optimization methods and evaluation strategies should be developed to better fulfill the urban synthesis. It is also a future expectation for the computer to learn from the urban designers and from their revised urban layouts so that better urban layout solutions can be generated.

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A PARAMETRIC ANALYSIS PROCESS FOR DAYLIGHT ILLUMINANCE

The Influence of Perforated Facade Panels on the Indoor Illuminance

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Abstract. BIM modelling systems and graph-based modelling systems have been widely used in the architecture design process recently. Based on the systems, an alternative approach to study the influence of perforated façade panels on the indoor illuminance by using a parametric performance analysis in a practical architectural project is proposed. The workflow we developed makes the modelling process faster, more accurate, and easier to modify. From the circulation of modelling-to-analysis process, the performance can be compared, feedback can be generated. Accordingly, optimized design can be concluded. This study suggests an analysis method to evaluate the indoor illuminance performance in the early design stages. The simulation is not a conventional typical in-depth one, but a practical method to immediately evaluate the performance for each design alternative and provide guidelines for design modification. Moreover, the first generation of digital modeling programs allow designers to conceive new forms, and allow these forms to be controled and realized. It reacts to the conference theme by presenting a protocol for a digital workflow in the early stage of the design development.

Keywords. Daylight illuminance; BIM; parametric sustainability; parametric modelling; facade panels.

1. Introduction

Nowadays, BIM modelling systems and graph-based modelling systems have been widely used in the architecture design process (Eastman et al. 2009). Meanwhile,

as sustainability has received attention continually in recent years, relative analysis is sometime needed in the early stage in design process. The previous sustainable analysis may require the establishment of new models because of the software environments. The simulation time are usually long and models are hard to be modified in some platforms. Therefore, this can be complicated and time consuming, which affects the efficiency of architecture design process. In our study, we propose an alternative approach to study the influence of perforated facade panels on the indoor illuminance by using a parametric performance analysis based on graphic and associated models.

The study is part of a practical architecture design project. This design is for a real project of a Natatorium in the city of Wuhan, China. The Natatorium is located west of the Huangpu Hall, an auditorium on the Huangpu Road in Jiang'an District. The investment for this project is about CNY22 Mio giving the project a very tight budget. The Natatorium has three levels with an architectural area of ca. 6,250 square meters. It is designed for 400 people to use. The number includes swimmers, audiences, and staffs. The swimming pool has ten 50 meters standard lanes. The main body of the Natatorium can be divided to the auxiliary part and swim hall. The auxiliary part has a three level high structure associated with the swimming hall. The swimming hall is a large-span space, using the steel-grid roof.

For the design of facade, perforated aluminium and ceramic panels are used. It is a double-skin facade with ordinary cement walls inside and perforated aluminium panels installed as the outer layer (He et al. 2012). In this work, the method for the façade will be present. Parametric modeling is developed for daylighting simulation. The main objective of the process and algorithm is to evaluate the illuminance performance of the façade, composed of a series of perforated openings that actuate in response to dynamic daylighting.



Figure 1. The 3D model of the natatorium. The major part of the modelling of the Natatorium has been done in Revit. The model is divided into several child models which are connected to the main model.

2. Sustainable Design

For this project, we use BIM and parametric modelling methodologies paired with a simplified illuminance calculation method to assist our design (figure 2). This is not the first time we make use of this methodology in such architectural projects (He & Schnabel 2016a). From our previous experience, this methodology not only offers benefits during the design phase, but also further down the track during construction and management (He & Schnabel 2016b).

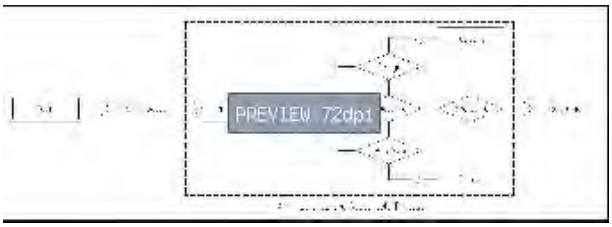


Figure 2. The workflow of BIM and parametric modelling methodologies paired with the illuminance calculation method to assist the design.

From the beginning, aspects of sustainability have been taken into consideration (Huang et al. 2004). Information about local climate, existing circumstance of the site and architectural standards especially the *Green Building Standard* are included in the initial analysis. In communication with clients, requirements, detailed functions and expected performance are determined to guide the initial design phase. During this, several analysis models have been generated.

3. The Modelling Process

In this section, we present the modelling process which includes the natatorium and its facade. Software tools of *Autodesk Revit, Rhinoceros 3D* and *Grasshopper3D* are applied in this project. In the case of complex application such as sustainable analysis, conversion processes are often involved in the modelling.

3.1. THE MODELLING OF THE NATATORIUM

The major part of the modelling of the Natatorium has been done in Revit. The model is divided into several child models which are connected to the main model. Several parts of the design are developed by different departments of the architectural firm. Then the parts are all assembled into a complete 3D model the natatorium. For the illuminance analysis, it is mainly done in the software environment of Rhino and its plug-ins. So we convert the BIM models to the format that can be edited in Rhino. Before import, the models are simplified to reduce the computing needs of the software. The models are modified further in Rhino to fit the analysis environment. The reasons of doing so are: first, this can improve the analysis efficiency; second, in this case of illuminance analysis, physical and graphical information are the major part needed from the BIM models.

3.2. THE PARAMETRIC MODELLING OF THE FACADE

The modelling of the facade can be done in the environment of Rhino and Grasshopper. For the generation of the openings of small holes on the panels, using the parametric method is efficient and suitable for comparative research (Schnabel 2007).

Our idea is to generate the single facade panel first, and then assemble them together. For the perforated panel modelling, the main strategy is to create the arrangement of points to locate the positions of openings. Then the shape of the openings can be defined by using certain algorithm before attaching them to the lo-

cation (figure 3). In Grasshopper, we can use the array algorithm to create a group of points. The horizontal and vertical number of the points can be defined by the inputs related to integer parameters. As the openings are in the shape of circle in this project, the circle component is introduced to create the round holes on the panels. Then we use the move command to duplicate the holes by attaching the circles to the array of location points. The generation process at this stage is not complicated, but it has the advantage in adjustments of the openings arrangement, which is suitable for iteration simulations and analysis. For example, by changing the parameters, the radius and the arrays of the round holes can be adjusted accordingly. The perforated density and arrangement of the panels can be modified in this way.

Moreover, this method can provide the big potentials that allow us to create complex facades and analyse them further by modifying the algorithm adopting different modules. This will be discussed in the following sections.



Figure 3. The perforated aluminium sheet model generated by parametric modelling. In Grasshopper, the array algorithm has been used to create a group of points. The circle component is introduced to create the round holes on the panels. Then the move command has been used to duplicate the holes by attaching the circles to the array of location points.

4. The Illuminance Analysis Based on Parametric Modelling

In this section, we explain the illuminance analysis process.

First, for the illuminance performance, we need the criterions to guild our optimization. In this case, for indoor illuminance evaluation, the criterions comes from the standards formulated by relate institutions in China. For example, in 'Code for design of civil buildings (GB50352-2005)', 'Standard for daylighting design of building (GB50033-2013)', there are requirements for different indoor environments according to their functions. It has been defined the lighting coefficient and natural illuminance of the facade in the criterions.

Second, for analysis, the software tool *DIVA* is introduced. It is an optimized daylighting and energy modelling plug-in for the Rhino. The plug-in was initially developed at the *Graduate School of Design* at Harvard University and is now distributed and developed by *Solemma LLC*. DIVA allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes. The simulation core of DIVA comes from the well-known software tools *Radiance,* which has been widely recognized as a suite of programs for the

analysis and visualization of lighting in design.

After the parametric generation of the panels, their performance can be tested and compared. In our study, the variable parameters include the horizontal numbers, vertical numbers and the radius of the round openings, which can be defined in different sizes. For comparative study, we can set two parameters unchanged at first, and adjust the last parameter. A series of simulation for the panels can be done one by one. After this, the tendency of the results can be analysed. Then different parameters is chosen to be adjusted for repeating the analysis. This preliminary iteration study can help to locate the relative available parameters of the facade panels. Base on this, we can select the subjects for further study. In our case, for example, the panels with vertical number of 100, horizontal number of 8, and holes of radius of 30mm ("V100-H8-R30"-panel), as well as the other panels are analysed (figure 4).

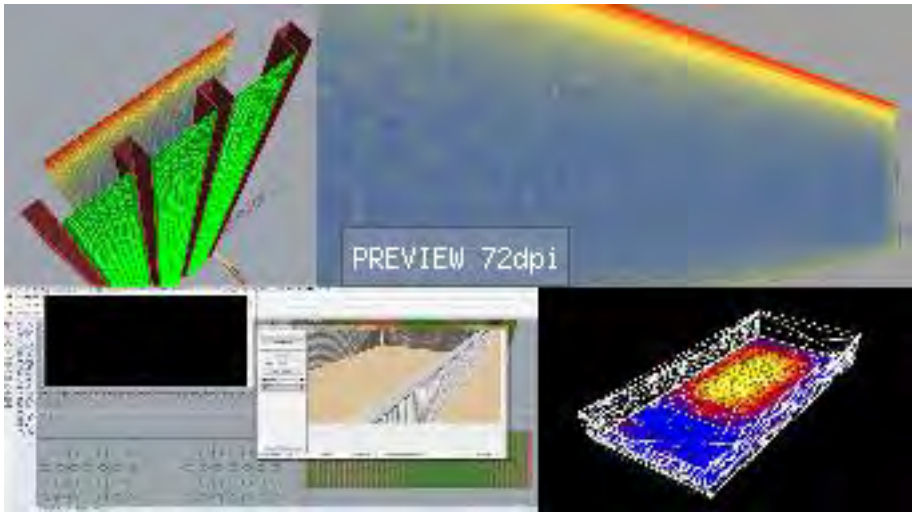


Figure 4. The daylighting simulation based on parametric modelling of the perforated panels. Different parameters is chosen to be adjusted for repeating the analysis. This preliminary iteration study can help to locate the relative available parameters of the facade panels.

To study the influence from the facade to the indoor illuminance further, the simulation is done for the interior environment. DIVA is used to complete the visualization analysis under the natural illuminance situations from January to December. In a series of analysis, we set the simulation time at 3:00 PM on 15th day in every month, as three o'clock in the afternoon is usually the time that the natatorium is occupied most according to the common situations. All simulations are set in a fixed view angle that results can be compared conveniently. The visualization simulation can help to better understand the natural illuminance in realistic environment in every month all over the year. References can be set up for architects to evaluate their design.

5. Results and Discussion

For the selected subjects after the initial filtration study of the facade panels, our illuminance simulation concludes they can meet the requirements. The results of the illuminance intensity distribution on the different facade panels have been compared.

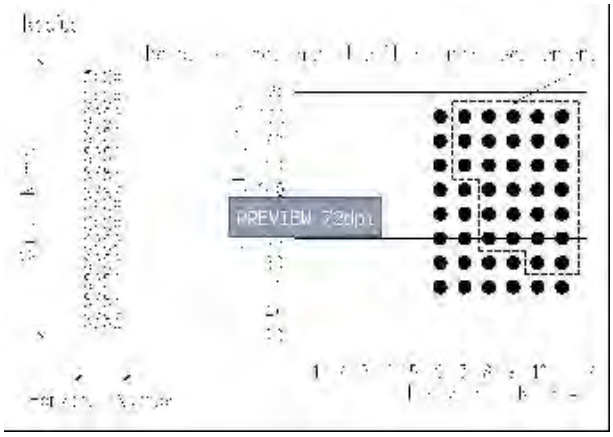


Figure 5. Left: The definition of the panel parameters. Right: The panels that have been studied and the panels that meet the illuminance requirements. .

In our case, a series of panels with certain parameters has been analysed. As it is shown in figure 6, the calculation results of panels with vertical number of 100, horizontal number of 8, and holes of radius of 30mm ("V100-H8-R30"-panel), as well as the panel with vertical number of 100, horizontal number of 8, and holes of radius of 40mm ("V100-H8-R40"-panel), vertical number of 160, horizontal number of 8, and holes of radius of 40mm ("V160-H8-R40"-panel), vertical number of 160, horizontal number of 9, and holes of radius of 40mm ("V160-H9-R40"-panel), vertical number of 160, horizontal number of 9, and holes of radius of 30mm ("V160-H9-R30"-panel),and vertical number of 200, horizontal number of 11, and holes of radius of 30mm ("V200-H11-R30"-panels) have been presented. Specifically, figure 5 has shown the panels that have been studied. For the radius of the openings, the situations with the radii of 30mm and 40mm have been concerned. The panels that meet the illuminance requirements have been presented in figure 5. The value differences on specific positions of the panels are of an acceptable small range. For the average illuminance on the selected panels, they are almost the same.We find that these samples all meet the requirements of the building-code. But the opening size should be considered for good appearance, the manufacture simplicity and the production economy of the facade panels. In this case, the panel with specific parameters (V160-H10-R30) is recommended. This allowed us to develop guidelines for the facade panel manufacturer to produce the aluminium panels.

To improve the illuminance performance further, we can modify the generation algorithm to change the opening sizes in a defined range. This leads to letting more

or less daylight into the indoor space by controlling the parameters. Our strategy is to create interference geometries first. Second the distances within openings and geometries can be calculated. Then we can use the values to define the sizes of each opening through the scale components. As the Figure 4 has illustrated, the sizes of the openings change gradually according to the position of the interference geometries we created parametrically.

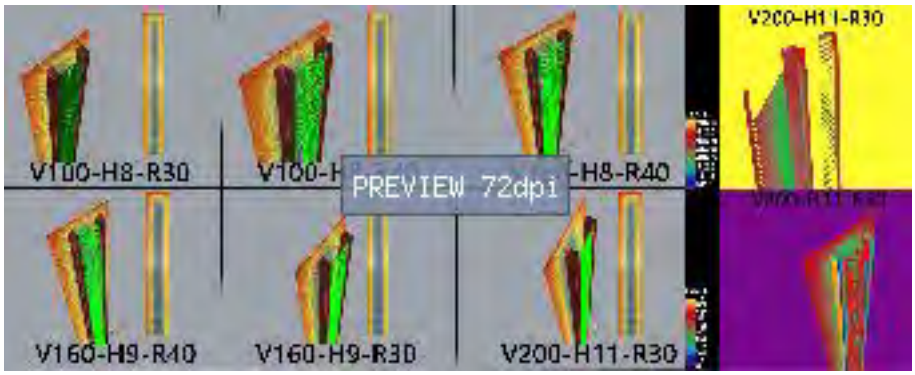


Figure 6. The illuminance calculation results of "V100-H8-R30"-panel, "V100-H8-R40"-panel, "V160-H8-R40"-panel, "V160-H9-R40"-panel, "V160-H9-R30"-panel, and "V200-H11-R30"-panels. The daylight and radiation intensity of the "V200-H11-R30"-panel calculated on specific day is shown on the right.

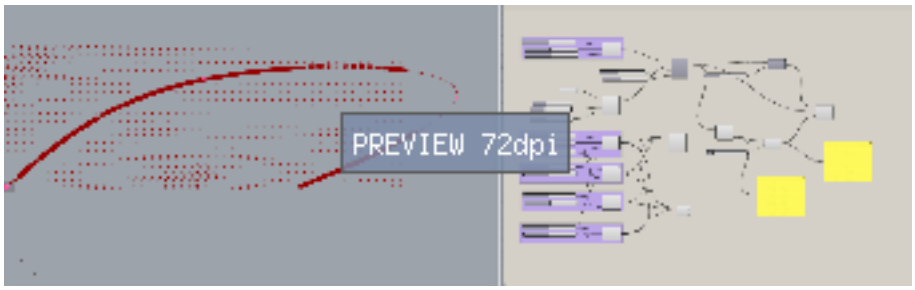


Figure 7. The modified algorithm helps to optimization of perforated arrangement. The sizes of the openings change gradually according to the position of the interference geometries we created parametrically.

6. Conclusion

This study suggests an analysis method to evaluate the indoor illuminance performance. The simulation is not a conventional in-depth one, but a practical method to immediately evaluate the performance for each design alternatives and provide guildelines and instant results for modification on the early stage. Our simulation approach is based on both the associative and graph-based models. In sum, the contribution can be summarized as follows:

(1) Our study has developed an alternative approach to study the influence of perforated façade panels on the indoor illuminance by using a parametric performance analysis. This modelling-to-analysis process can be repeated efficiently in

order to compare the performance of models with different parameters. Based on comparison and circulation, optimized design can be concluded according to the feedback. By setting up the link of graph-based system and associative system, we've tried to take the best advantage of the BIM models for multiple use.

(2) The study has attempted to explore a parametric design-analysis workflow in order to determine the advantages of parametric design in studying real-time changes in building design. Compared to conventional workflow, it is easier possible to design a performative-responsive façade using parametric design. As it allows for efficient editing the model in any stage of the design process. With the established relationships between parameters in parametric design, architects have better dominance on the project.

(3) Based on our research outcomes we can give our design guidelines to the facade panel manufacturer who produces the proposed aluminium panels. As the models are developed on a parametric computational platforms can seamlessly be employed to manufacture the facade panels, e.g. industrial robots.

(4) The simulations can improve the understanding of the natural illuminance at any given times during a year allowing architects to evaluate their design during the early design stages.

Acknowledgements

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FUNCTIONALLY GRADED ARCHITECTURAL DETAILING USING MULTI-MATERIAL ADDITIVE MANUFACTURING

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Abstract. The paper presents a future architectural detailing strategy enabled by the design of functionally graded materials (FGM). In specific, our proposal suggests the possibility of removing mechanical fasteners and adhesives from joint details. This is achieved by combining the principles of interlocking joineries found in traditional timber structures and current Multi-Material Additive Manufacturing (MMAM) technology to materialise FGMs. FGM belongs to a class of advanced materials characterised by variation in properties as the dimension varies by combining two or more materials at a microscopic scale (Mahamood et al. 2012). FGM is ubiquitous in nature and, when properly designed, can exhibit superior performance characteristics compared to objects comprised of homogeneous material properties. With the aim of developing interlocking details with improved performance, reliability, and design flexibility, we focus on controlling material stiffness, joint fitting, and geometry through the design of the microscopic material layout. A case study design will be presented to illustrate the process.

Keywords. Functionality Graded Material; Multi-Material Additive Manufacturing; Architectural Detailing; Interlocking Joints.

1. Introduction

In the past century, structural detail design has been dominated by the use of mechanical fasteners and/or adhesives to connect homogeneous elements of industrial materials like steel and/or concrete. On the contrary, historical heterogeneous timber structures mainly employ the use of interlocking joints in their detailing. Interlocking details can be viewed as a design principle to join and connect multiple individual structural components without the application of mechanical fasteners and/or adhesives. The design of such details involves the various connecting pieces of a structure to have carefully designed geometry and intelligent material usage. Although traditional interlocking joints that have been developed and refined over centuries exhibit an enormous body of material knowledge, its application to buildings are limited today and often requires mechanical fastening. This is

because of the multiple factors involved in ensuring the structural performance of interlocking joinery made of natural timber material. The factors include, but are not limited to, moisture content, knot location, grain irregularity, and wood species and growth condition of the timber, as well as the skill level of the craftsman in producing joints with appropriate accuracy and tolerance (Erman 2016).

In this context, our research takes a view that microstructure and its composition of every material, including that of wood, will be designed and custom-tailored to improve its performance and reliability in the near future (Messler 1995; Messler 2000). These materials are called Functionally Graded Materials (FGM) and one of the methods to materialise such concepts is accessible today through Multi-Material Additive Manufacturing (MMAM) technology.

We envision that by designing material stiffness and fitting tolerance, the interlocking joints can be re-introduced into architecture as a viable detail solution with improved performance and reliability as well as with more design flexibility. The paper provides an overview of FGM and related studies with respect to material stiffness/strength and fitting design, followed by a particular case study of furniture design with interlocking FGM details.

2. Functionally Graded Materials

FGMs are characterised by a variation in properties within a single material composition and provide a selective juxtaposition of multiple materials within an object. Through careful design of the material layout, they offer superior mechanical, thermal, optical and chemical properties of their single material homogenous variants of uniform properties (Suresh 2001; Watanabe et al. 2003).

The concept of FGM was first proposed in the 1980s for the Japanese aerospace industry to develop reusable rocket engines that required material to withstand the large difference in internal and external temperatures across a thin cross-section of a thermal barrier. (Sobczak & Drenchev 2013; Udupa et al. 2014). This has given rise to a special class of heterogeneous composite materials which have been engineered to meet practical problems and involve the combination of two or more materials bonded together in the microscopic scale (Mahamood et al. 2012). More recent research trends of FGM have been propelled by the introduction of MMAM which eased its fabrication. Examples include the development of tunable shape memory polymers and alloys, actuators, energy harvesting/generation and recreation or modification of inherent material properties and behavior found in nature and biology etc. (Cutkosky & Kim 2009; Djumas et al. 2016; Ferreira et al. 2016; Ge et al. 2016; Guttag & Boyce 2015; Oxman et al. 2011).

Next, we look into some of these examples that are relevant to the domains of our research: (a) Material Stiffness and Strength and (b) Fitting.

2.1. MATERIAL STIFFNESS AND STRENGTH

Material stiffness, in the design of traditional timber joints, is often physically and visually manifested in the alignment of the timber grain with respect to the loading direction. When applied to FGMs, the act of enhancing the stiffness of materials gives rise to the development of Graded Structural Materials (GSM),

which have been widely explored in the fields of material science, engineering and manufacturing (Ren et al. 2014).

In recent literature, von Mises stress is used as criteria for the design of the material composition within FGMs. For Hedia & Mahmound's work, the microstructure of a functionally graded dental implant was designed with respect to local stress distributions in the bone in the vicinity of the implant. Finite element analysis and material optimisation were performed to assign volume fractions and rule of mixtures of the ceramic and metal composition of the FGM implant (Hedia & Mahmoud 2004). Similarly, Wu et al.'s study of the synergetic strengthening of gradient metals used von Mises stress to determine the isotropic strengthening with the complex gradient structure (Wu et al. 2014). This had led to the prediction of the strength of the composition based on the rule of mixture, and subsequently, provide a strategy for designing for such FGMs.

2.2. FITTING

For solid timber joints, the principle of shrink-fitting, a type of interference fitting, is employed by compressing or shrinking one member into another in order to create a contact pressure and friction force at the interface of the two assembled parts. Localised stresses are concentrated at the contact surface of the joint and provide a stiff load path that does not weaken significantly by the shrinking/swelling of the material over time (Wang & Lee 2014). As for other materials, this technique could be performed in the presence of external stimuli, as done in the methods of cold expansion, heating or electromagnetic riveting (Cao & Cardew-Hall 2006; Chakherlou et al. 2009).

To the best of our knowledge, there have yet to be specifically designed FGMs in this field of application. Nonetheless, the use of composites in interference fitting joints has been recognised as an efficient mechanical retention system in terms of weight reduction (Lee & Lee 2005). Lee & Lee's paper demonstrates the use of a laminated composite tube in interference fitting and has performed physical experimentation and finite element analysis to evaluate the localised stress and transmission of the torsional load within the component (Lee & Lee 2007).

3. Case Study: Table Design

Merging the principles of functionally grading materials for material stiffness and fitting, we present a process and our considerations pertaining a table design composed of interlocking joints fabricated using MMAM (figure 1).

The small coffee table is composed of 5 elements connected via interlocking joints without the use of mechanical fasteners or adhesives. The cantilevering composition of the table is designed to illustrate the use of geometry and material to withstand structural loads. Though our focus here is material design for interlocking joints, first, we briefly touch on the overall geometric design - a critical aspect for such detail design.



Figure 1. A Full-scale prototype of the interlocking table. (photograph by Jansen Teo photography).

3.1. GLOBAL GEOMETRY DESIGN FOR INTERLOCKING JOINTS

An interlocking joint and its material design cannot be considered in isolation from its overall structure. Assembly and disassembly directions require careful consideration together with the overall structural integrity. This is because the assembly insertion direction of interlocking joints is the direction in which the interlocking structures cannot transfer loads. The middle joint (Joint A, figure 2) is designed based on a traditional Japanese joinery called Kone-Hozo-Katamuki-Doutsuki. The joint is typically used to connect columns and beams in an orthogonal configuration and is considered good at taking axial compression and bending moment. The geometry of this traditional joint is modified so as to fit the desirable spread angle of the table legs (figure 3). At the same time, the tilt of this assembly set ensures the pull-out force (force acting on the disassembly direction) to be resisted by the ground. The assembly direction of the custom designed top joint (Joint B, figure 2) is near perpendicular to the table top assembly direction. The combination of the perpendicular assembly directions of two elements acts as a lock to prevent disassembly. When considering natural timber as a material for the joint, joint geometry is constraint by the grain orientation. However, as our approach proposes to design the material stiffness and joint fitting, we can achieve the proposed geometric flexibility. The overall design has undergone several iterations of prototyping and Finite Element (FE) Analysis before achieving its final form.

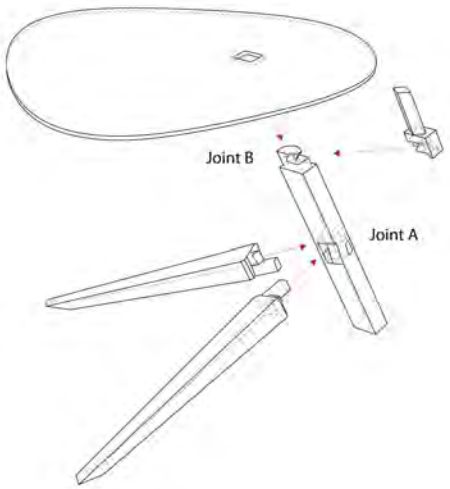


Figure 2. The interlocking table is composed of 5 elements without mechanical fasteners or adhesives.

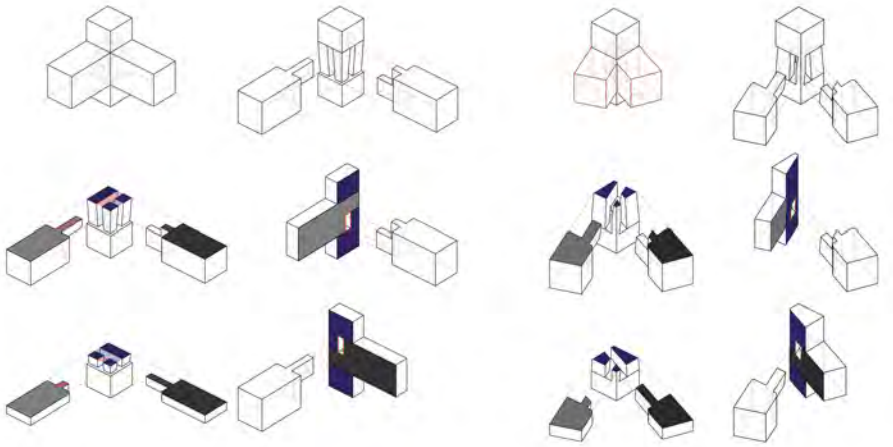


Figure 3. Left two columns: diagrams of traditional interlocking joinery; Right two columns: diagrams of modified joinery structure for the interlocking table.

3.2. DESIGNING FOR MATERIAL STIFFNESS

The FGM design for the table legs (figure 4) was considered following the global geometry design. The scope here is to design FGM/GSM based on full 3D solid contact FE analysis result. In particular, the von Mises stress gradient and principal stress values were used to determine the microscopic material layout using multi-material Voxel Printing, supported by the OBJET Connex 3D printer (OB-

JET). The machine uses PolyJet Matrix Technology where materials are dispensed from designated micro-scale inkjet printing nozzles at approximately 600dpi. The primary materials, excluding the support material, are the Vero and Tango-series where Vero-series materials are thermoset polymers, while Tango-series materials are elastomers. By combining those two very different types of materials, the printer offers the capability of producing objects with varying elasticity. And as such, it is possible to design and prototype structurally graded design solutions. Our method uses Rhinoceros (Robert McNeel & Associates) as CAD modelling platform, ABAQUS (Dassault Systèmes) for FE analysis, a software tool we developed for material modelling based on FE results, and Monolith (Autodesk) for rasterization.



Figure 4. Fully 3D printed FG interlocking table legs with MMAM. White areas indicate the location of stiff material. (photograph by Teo Jansen photography).

As discussed in section 2, the notion of FGM / GSM has been well studied and some of the hardware to materialise the concept is offered by MMAM technology. However, fabrication of FGM for architectural applications is not a trivial task. This is primarily due to the access to the technology being limited by the way in which current modelling and simulation tools represent, exchange, and process information (Jackson et al. 2002). The challenges involved in the computational workflow including the data structure to materialise FGM with MMAM have been discussed in detail in our previous paper through a theoretically well-understood case of a cantilever beam structure (Kaijima et al. 2016).

The initial global geometry, including the table legs, was modelled in a CAD software using the boundary representation (B-Rep). Subsequently, we performed pre-processing operations for FE analysis such as assignment of material properties, loading and boundary conditions as well as discretization of the solid into

polyhedral elements. The FE analysis calculation produced results consisting of response values calculated at vertices/nodes and cells/elements (figure 5). Typically, for post-processing purposes, cell results are extrapolated and stored at vertices. This information per vertex becomes the input for the material design step. Each vertex contains positional information as well as any FE result information such as {x, y, z, s11, s22, s33, s12, s13, s23, vm} where s11 to s33 denotes normal stress tensor values, s12 to s23 denotes shear stress tensor values and vm denotes the von Mises stress value. We have overlaid several analysis results of anticipated loading conditions for the table design.

The next step involved Voxelization of the FE results. This is to convert polyhedral mesh structured data into voxels that are a common data structure for MMAM. The step requires the computation of the integrals over the intersection volumes between cubical voxel cells and the input polyhedral (Kaufman and Shimony 1987) It is important to note that voxelization should be performed at best-fit bounding box of the element of interest to capture the highest data resolution with computational efficiency.

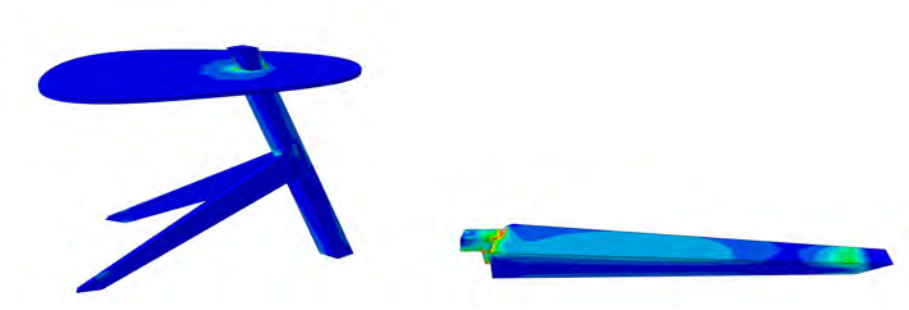


Figure 5. Finite element solid contact analysis results. Left: A visualization of normalized von Mises stress of the table under self-weight. Right: A visualization of normalize von Mises stress of a table leg.

Finally, for the material design process, von Mises stress information was normalised into the unit range. With this data attributes, we interpolated material composition such as nvm of 0.0 maps onto 100% elastomer material, 1.0 maps onto 100% thermoset material while nvm = 0.5 represents a ratio or 1:1. When the von Mises data distribution is too skewed or noisy, we use statistical methods to equalise the data. In addition, we extracted principle stress streamlines and assigned the thermoset material, that is analogous to fibre reinforcement or grain orientation, while the thickness of the streamlines reflects the stress values. In this particular instance, the streamlines were carefully designed with the criterion of both aesthetics and structure.

3.3. DESIGNING FOR FITTING

Similar to the design of microstructure of each table leg to enhance material stiffness, it is possible to modify the material layout in order to enhance fitting of ex-

isting applications (figure 6). Adopting the shrink-fitting principle of interlocking wood joints, the ends of the table legs which interface with the middle member are designed by juxtaposing a flexible compliant material (elastomers, Tango) within a stiffer outer shell (thermoset, Vero).



Figure 6. Photograph of a joint detail. A flexible compliant material is encased within a stiffer outer shell to improve fitting. (photograph by Jansen Teo photography).

Such a material composition allows the compression of the 'male' segment of the joint to facilitate the insertion into the middle member. Once interconnected, the uncompressed flexible material returns to its original state, locking the joint in place through contact pressure and friction force that acts locally on the interconnected surfaces of the joints. This also increases the pull-out force of the inserted joint, making it difficult to disassemble even if a force opposite to its assembly direction were to be exerted. Nonetheless, as the current design involves the arbitrary placement of the region of more compliant material within the stiffer outer shell, it is to be noted that further studies will be done to predict the behaviour of designed FGMs in the context of fitting applications.

4. Conclusion

The paper presents an approach to future Interlocking detail design based on the principles of designing Functionally Graded Materials (FGM). Our design case study of a furniture suggests a possibility of removing mechanical fasteners and adhesives from joint details by designing material stiffness, fitting, and geometry.Although current Multi-material additive manufacturing technology, due to its material selection and scale, is used for prototyping and not immediately deploy-

able for buildings, developing design approaches with FGM could significantly impact the future architectural and structural design. To this end, we have designed and built a pavilion to demonstrate its applicability in architecture, which will be presented in our subsequent publications.

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INTEGRATING COMPUTATIONAL DESIGN AND TRADITIONAL CRAFTS

A Reinvention of Bamboo Structures

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Abstract. Abstract: This paper searches for an alternative design method of integrating traditional material craft and computational design. It begins by analyzing Chinese philosophical view of nature, and proposes a natural design built method. The paper demonstrates the idea with two bamboo structure projects. In China, bamboo is closely linked to culture values and traditional craftsmanship. The projects research on the formation logic of bamboo system, and employs computational design method to activate the system formation. The projects strive to investigate computational design with unique eastern characteristics, to find out how it can help to reinvent its traditional values, and to search for a unification of formation logic and material sensibility.

Keywords. Craftsmanship; materiality; form finding; bamboo.

1. Introduction

In the view of Chinese Philosopher Laozi, "Dao" or "Way" organizes the naturalness (ziran); therefore, he called for nonaction (wuwei), not to interfere natural's Way. In such point of view, design is a formation process emerged out of natural forces. This design research proposes to study the "Dao" of bamboo, to understand the material's intrinsic values and the system forming logics, and to use them to inform the emergence of the material construction. This paper demonstrates two projects working with bamboo structure. Both projects take into account the traditional culture and method of working with bamboo, one borrows the traditional paper umbrella structure prototype, the other adapts the bamboo heat-bending method. Materiality consists of the material's behavior and its cultural understanding. The projects investigate how materiality affects the material system form finding. Computational design method is used to simulate the formation of the bamboo system.

Laozi's eastern thinking has influenced Heidegger's view on material and technology. Heidegger questions the utilitarian aspect of technology, which is deviated from the true existence of material. He argues for a poetical dwelling, which considers poetry as manifestation of truth restored to its artistic dimension (Leach 1997). This research project investigates an alternative design method of integrating traditional material craft and computational design method, and search for a unification of formation logic and material sensibility.

Computational design technologies expand the performance of bamboo structure. It is not a neutral tool in the design process, but it plays an important role in the forming of a digital / handcraft hybrid system. This research project strives to investigate computational design with unique eastern characteristic, to find out how computational design can help to reinvent traditional values.

2. Bamboo

Bamboo is a traditional material in China. It is closely linked to Chinese traditional culture and material craft. Bamboo has very strong fiber, therefore, in Chinese culture, bamboo symbolizes integrity, endurance, and purity; it represents the characteristics of a Chinese gentlemen. Such characteristics also makes it a common material for traditional craft in China, such as basket, umbrella, and in some area, building structure. Bamboo is also a green material, and it has enormous industrial values. Traditional craftsman has accumulated indepth knowledge and techniques in working with bamboo, and has acquired intimate understanding of its material performance. But because of globalization and industrialization, the handcraft culture is disappearing. This research tries to learn from the traditional craft, investigates the bamboo's intrinsic values, strives to find a way to inherit and reinvent this traditional value (figure 1).



Figure 1. Traditional paper umbrella craftsmanship.

3. Learning from Material Craft

In traditional material craft, the making of form and materialization is an integrated process. Architecture has been focused on the manipulation of form, and usually the materialization comes after. Achim Menges criticizes the separation of form definition and materialization:

"Since the Renaissance the increasing division between processes of design and making, as proclaimed by Leo Battista Alberti, has led to the age-long development of and increasing dependence on representational tools intended for explicit, scalar geometric descriptions that are the same time serve as instructions for the translation from drawing to building. Inevitable, and with few exceptions such as Antoni Gaudi, Frei Otto, Heinz Isler and some others, architect has embraced design methods that epitomize the hierarchical separation of form definition from materialization. In today's practice digital tools are still mainly employed to create design schemes through a range of design criteria that leave the inherent morphological and performative capacities of the employed material systems largely unconsidered. Ways of materialization, production and construction are strategized only after a form has been elaborated, leading to top-town engineered, material solutions that often juxtapose unfitting logics" (Menges 2010).

In this bamboo research project, bamboo's structure performance and traditional craft culture are the driving forces for the emergent of material form. The bamboo research projects are inspired by the traditional way of working with bamboo from rural China such as heat bending and paper umbrella making. We were inspired from such techniques and employed computational design methodology and the result is a reinvention of the ancient material system (figure 2).

As digital software and tools change the way we think, design, and build, they allow us to achieve what was not possible with conventional methods. On the other hand, the sense of human touch is lost. In our bamboo research projects, Cloudscape learns from traditional bamboo heat-bending craftsmanship, and it is digitally form-found with the consideration of the bamboo material behavior; it creates an arbitrary load structure of 40 meter wide, 50 meter long, and 9 meter tall. The Parametric Umbrella is inspired by Chinese Paper Umbrella craftsmanship. It borrows the umbrella structural frame system, and it is reconstructed and reconfigured with computational design logic. Both projects strive to investigate a new design approach with the integration of bamboo material behavior, computational design logic, and traditional craftsmanship.



Figure 2. Reinvention of traditional paper umbrella.

4. Computational Design Catalyst

Computational design enhances the design and performance of bamboo system. Cloudscape is a digital designed, hand crafted, pure bamboo structure. It is the graduation pavilion of the China Academy of Art in Hangzhou, China. In this design project, we try to help bamboo to find its true identity. We utilize bamboo's bending behavior to create a long span structure, which has to accommodate at least 2000 peoples. In China, traditionally bamboo structure is designed and built with the Cartesian grid, ignoring the bending performance of the material. Traditional bamboo weaving crafts such as bamboo basket, involves the bending of bamboo. However, it is operated in a smaller scale and usually required mold to fabricated it.



Figure 3. Cloudscape structural study.

The difficulty of making large and free-form bending bamboo structure lays in not only the design of double curvature surface, but also in the coordination and bending curvature of bamboo members during the construction. More difficult part of the design experiment is that bamboo structural behaviors varies depend on bamboo's age, type, place of origin, etc. There is no bamboo structure standard nor preexist data that we can follow. Therefore, in the early design process, we constructed 3 different prototypes to test the bamboo's material performance, to determine the maximum height, maximum span, and minimum bending radius. Much performance data can be coordinated into the computational model to simulate the free-form bamboo structure with arbitrary loads. In addition, in the Cloudscape graduation pavilion, every single curve has more than 2 different bending direction. Such double-curvature, free-form structure is difficult to design with conventional method. With the help of computational model, we were able to form-find the complex structure form with the fixed edge conditions.

The digital structural model is computed with Karamba, a parametric structural engineering software. It simulates the performance of hanging chain net model to find balance of internal arbitrary stresses. The form is first modeled as a shell, calculated by Kangaroo physical engine. It then computes the gridshell pattern with Karamba under the global condition of gravity. The result is a system of arbitrary 3-dimential curves, which are the stress lines under the optimum force balance in the system (figure 3).

Digital model also outputs fabrication data, clearly defines the position, length, height of each bamboo, allowing craftsman to construct with traditional low-tech methods. Therefore, computational model plays a critical role in this unconventional bamboo gridshell structure. It preserves the authentic hand's touch of the bamboo construction, and it also expands the performance of bamboo to create a dynamic space and large span structure.

We invited craftsmen from a local town Anji. Following the shop drawings generated by our computational models, they heat-bend the bamboo on site, and cool it down with water to maintain the bending shape. Bamboo's intrinsic values are widely expressed in the design and fabrication process, it shows the reciprocal relationships between material, structure, and form.

5. Glocal Design Thinking

Digital design culture can gain benefits from cultural values and traditional craftsmanship. A materal's cultural understanding affects how the material is used and organized. Antoine Picon calls for the memory in our design culture (2010). Globalism contributes production efficiency as well as uniformity to our architecture industry. Unique culture and craftsmanship is lost. Wang Shu and Kengo Kuma found their design inspiration from the culture origin and local craftsmanship, which form their unique design styles. It becomes more important for the new generation of architects to trace our roots, to become a "glocal" citizen, with the understanding of global and local culture. Computational design becomes a new linkage between global and local material practices.



Figure 4. Umbrella system digital model.

The Parametric Umbrella is inspired by Chinese paper umbrella. Paper umbrella is a Chinese traditional craft. It contains deep culture values. Umbrella is not merely an object, and it also represents a space.



Figure 5. Umbrella pavilion.

The Parametric Umbrella project destroys the sign and objecthood of traditional paper umbrella, turns it into abstract surface in order to generate dynamic spatial system. The umbrella system use mathematic logic to control the variation of bamboo structure and spatial relationship. The system begins with the traditional paper umbrella structure prototype, and it's controlled parametrically with the anchor points (the columns), the height, and the surface direction (slope). The surfaces are formed mathematically based on those geometric constrains. The final form also emerges out of the materiality of bamboo. It spiral form provides structural rigidity, and created a flexible modular system (figure 4). Through the parametric control, this modular system can easily adapt different site conditions and functional needs; it creates an open, dynamic space that connects people and nature.

The computational design of the Parametric Umbrella has a strong local culture influence. With the intervention of latest design technology, it connects traditional craft and modern technology, local culture and global value (figure 5).

6. Logic and Sensibility

Computational design uses logic and deductive reasoning to construct model. It generates a dynamic system that controls the performances of architecture. The definition of performance, according to Yasha Grobman (2008), contains three dimensions: an empirical dimension, which focuses on directly measurable performances that usually related to physical data such as strength, temperature, the quantity of light, etc; a cognitive dimension, which focuses on the way human cognition can be translated into space, and conversely, the way space can be translated into human cognition; and a perceptual dimension, which focuses on the way

human perception can be translated into space, and conversely, the way space can be translated into human perception. Digital design is able to transcribe the empirical dimension with computer script; however, there is no direct way to engage the cognitive and perceptual dimension. In contrary to Frei Otto, Peter Zumthor takes a different approach in architecture materialization. He uses material to create atmospheres that return materials to themselves rather than some abstract meanings. Is it possible to translate the true materiality, as Zumthor describes "the things themselves", into computer code? As emerging technologies opens up new design opportunities, the design of form should not be separated from its materialization. Architects have to integrate material performance and sensibility in the design in order not to lose in the digital jungle.

With computer simulation, the empirical dimension of material performance can be integrated in the computation design process. In Cloudscape, intrinsic values of bamboo are used as parameters for digital design. On the other hand, Peter Zumthor argues for the poetic quality of material, which is another performance that digital design rarely able to incorporate. Zumthor asks for a return to the things themselves, expresses the importance of material in the real world:

"The material presence of things in a piece of architecture, its frame. That kind of thing has a sensual effect on me. And that is what I would call the first and the greatest secret of architecture, that it collects different things in the world, different materials, and combines them to create a space like this. To me it's a kind of anatomy we are talking about. Really, I mean the Word <body> quite literally. It's like our own bodies with their anatomy and things we can't see and skin covering us. The body! Not the idea of the body - the body itself!" (Zumthor 2006)

Traditional handcraft possesses intuition and material performance. Unlike computational abstract logic, it is attached to the human body and the material sensation. It adds a human touch to the computational reasoning model, and increases the cognitional and perceptional performance of the system. On the other hand, computational model provide a guideline for the organization logic which increase the material performance.

The bamboo material system promotes some kind of digital vernacularism that forms a hybrid system of digital design and vernacular craftsmanship. It deals with the relationships between handcraft and computer, man and machine, material and form, and provides a unique opportunity for the unification of the abstract logic and the poetic sensibility.

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BAMBOO CONCRETE SHELLS

An Adaptable Construction Method Using Onsite Materials in a Remote Location

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Abstract. This paper proposes an on site construction support system using digital techniques to solve the issue of logistical inconvenience on remote islands, where industrialized construction methods are absent. Transporting heavy machinery is costly and difficult in isolated rural areas. In addition, introducing materials from outside creates a heavy ecological footprint when building. Locally produced construction materials resolve many of these issues. To test the potential of building within these constraints a case study site on an isolated island of Japan, named Kuchinoerabu, was chosen. A concrete shell structure was created using locally sourced bamboo as reinforcement. Through the study, several technical issues are revealed. Significantly, there is broad variation in the material properties of bamboo, and reducing errors when using unskilled labor is difficult. The system nominally manages the following functions: 1) Synchronizing data between CAD and the materialized form; 2) Checking errors between the target form and the one that was actually produced; 3) Inputting material characteristics on site. 4) Making a structural analysis, and reflecting its execution during construction. These functions minimize the margin of error, and aid an unskilled labor force to work more accurately.

Keywords. Bamboo; natural material; digital construction.

1. Background and Social Problems

There are social issues when one attempts to construct buildings on isolated islands.The first problem is following; in remote places, especially rural area, there are few advanced construction devices, as well as heavy machineries. Skilled

labourers to operate general or specific devices for construction work are also missing. The second issue is the difficulty of transporting materials. Since the 20th century, factory made standardized/industrialized parts are used from design to construction. But on the other hand, in remote island there are few production bases, thus, the logistics becomes difficult. Shipping is expensive and would put a heavy burden on the site environment.Thirdly, an environmental adapting building is required ; Kuchinoerabu-island is set as the site, where there are extreme weather conditions such as fierce wind in typhoon seasons. The structure has to be structurally robust and utilizes local materials. In order to ensure the effectiveness of the proposed system, the building experiment was done in Kuchinoerabu-island. Located far away from Tokyo, reaching the site takes 1.5 hours on plane and twice transfers on ship. The place is known to have had extraordinary environmental conditions, including a volcanic eruption.

2. Bamboo Reinforced Concrete Shell by Digital Construction System

In this section, referring from existing research (Yamamoto et al. 2010), general idea of this building are explained.



Figure 1. Bamboo reinforced concrete shell.

2.1. WHY BAMBOO REINFORCED CONCRETE SHELL?

The project of bamboo reinforced concrete shell (figure 1) explores the topic of shell structure and its construction method, while in ordinary constructions steel are used as reinforcements. This project is the answer for three social issues raised above. Solution 1; Effortless construction.This surfacing by steel trowel method is much more effortless than form construction method, because it is able to reduce time to make form by sandwiching wooden panels. The required technique of this concrete placing method is relatively difficult for unskilled labors but can be reduced by using the proposed system. Solution 2; Low environmental impact. For the purpose of alleviating the environmental burden, the proposal attempts not to bring in external materials. So the wild bamboos that grow luxuriantly there are chosen for reinforcement for concrete. Fecundity of bamboo is very high, so that a wild bamboo forest can expand quickly. Appropriate consumption rate of the bam-

boo can bring positive effect for vegetation in there. Solution 3; High structural performance to respond to windy weather on the island, weight and strength of the material are required. The proposal employs concrete as the structure, instead of using only weaving bamboo straps. In addition, the unique character of bamboo straps of bending toughness in normal direction of annual ring because of fiber direction, has inspired the design to become a curved surface rather than a box-like form. In order to answer these requirements, a hypothetical design proposal is suggested and tested on that island (Inoue et al. 2009).

2.2. PROBLEMS WHEN CONSTRUCTING THE SHELL

When executing the three solutions, it revealed that 'errors' would be a serious issue. The problem of solution 1 where the human hand work may cause various errors such as when bamboo felling and timber-sizing it; when building foundations, when weaving it by handcrafting, when plastering with hand trowel. The problem of solution 2 is because of using local material; the material's uniformity can not be guarantee so each bamboo strip will slightly differ from others. This induct errors inevitably. The problem of solution 3 is where there are no parts division based on architectural idea, such as wall, ceiling in shell structure. This smooth surface does not have singular point; it may be structurally more stable. However, to materialize three dimensional surface into reality without guidance is hard for human. Thus, deviation between desired shell and realized shell would occur. As above, these three solutions generate 'errors'. In order to solve this problems, the design and build system is proposed here. That system is divided into two parts supplementally; first is a pre-construction method to make a CAD model which has an allowance range; second is during-construction method where data is checked with digital devices.

2.3. HOW TO SUPPORT WITH DIGITAL CONSTRUCTION SYSTEM

The concrete system is explained below.The aim of this system is to design a construction system that guarantees a building's construction quality even the subject (worker/machine, or those hybrid system) creates a discrepancy between the finished outcome and the original design, but that gap still lays within the possible allowance. The construction is considered "complete" when the worker corrects this misalignment created by unexpected site circumstances and decisions through adjustment informed by the system, whereas in conventional constructions, completion is defined as almost perfect material realization of building as designed in drawings, which often led to inferior quality as a result of this unrealistic management methodology (figure 2). As a methodology of this, 1) pre-adaptability and 2) post-adaptability, and 3) hybrid adaptability are assumed. The first method is referring to the design process that is before product materialize (construction). The idea that the objective data (geometry) originally contains the approvable range. The second method is mainly on construction steps. That is, having taken difference during construction steps and then operate to recover towards original object (can be geometry); one may have to break and rebuild the previous part, or modify the next part for recovering to original with admitting existing part. Thirdly, a hybrid method that takes the differences and then make a new target (can be a

geometry, can be an objective function) based on those conditions. In this method, materialized part is given up and re-calculate, which allows multiple possibility.

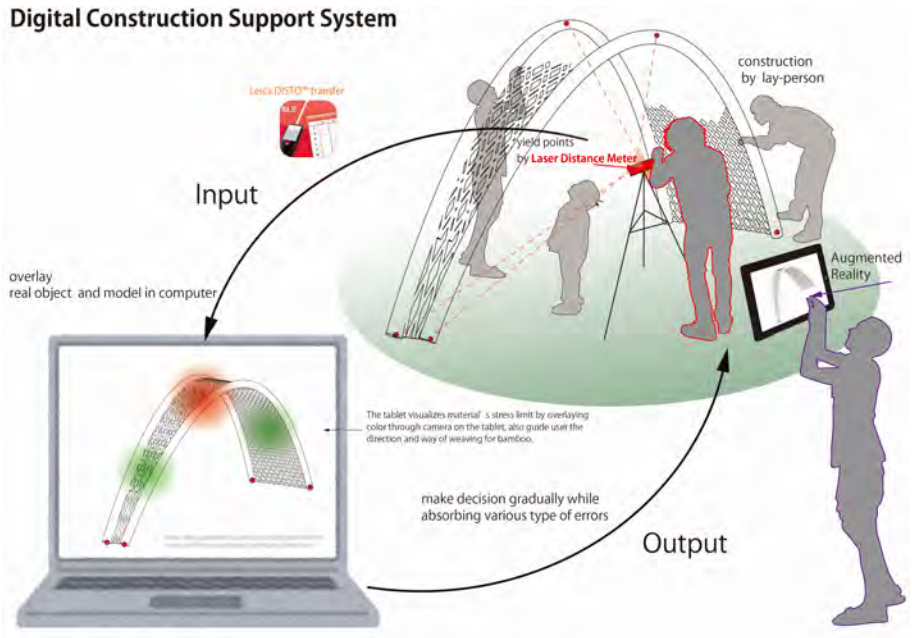


Figure 2. Digital construction support system.

3. Digital Construction Technology

In this section, concrete methods for digital design and construction are introduced. These includes how to make building construction with using data, but also relates to digital design too.

3.1. PARAMETRIC MODELING

The margins for construction of the bamboo-reinforced concrete shell are considered and parametric parts are determined. This parametric model offers pre-adaptability for the precision of the construction process. The actual parameters (figure 3) are: diameter of the base circle (1); location and diameter of the inner circle (2); range of an inflation of the base torus geometry (3); the used portion of the base torus angle (4); locations and shapes of the holes (5).

The surface of shell is surrounded by curved edges, which is called edge arches here. Each edge arch is made from two bamboo timber, start from the ground. The construction process starts from installing these edge arches. The length between point A and point B (figure 4) is calculated automatically. Thus the required material length can be seen immediately, then able to search from bunch of different material mountain.

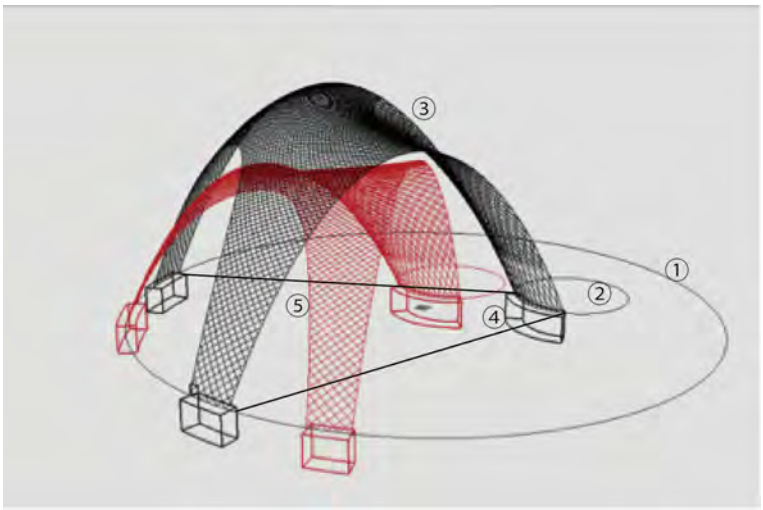


Figure 3. Parametric 3D model.

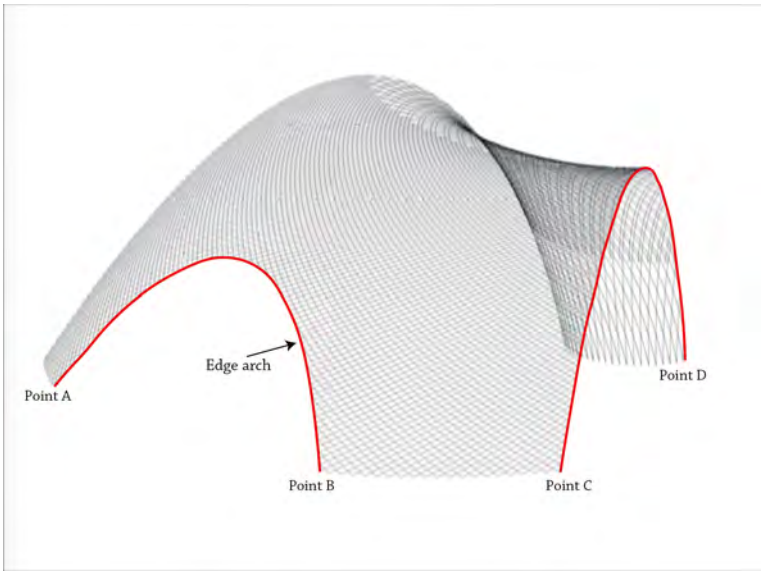


Figure 4. Automated calculations for the length of the edge arches.

On the torus structure, appropriate distribution of the bamboo (figure 5) is radial as in the (a). In order to verify this, (b) was made with the split bamboo whose width is same for the actual construction. From this experiment, it turned out that the concentrically twisted geometry is not suitable for bamboo. However, the radial geometry was successfully constructed. In the case of (c) bamboo breaks when the angle between the bamboo and the shell is too big, whereas in the case of (d)

the bamboo's elasticity is utilized as the bamboo is more in parallel direction with the shell (Yamamoto et al. 2010). However, in order to create a stable shell, the bamboos have to be crossed. When creating a concentrical geometry, the bamboo became perpendicular the surface of the shell on the upper part. Hence, this distribution of the bamboo is problematic. The curvature of geometry was calculated (e) on the 3d model and determined 60 degrees that is one of optimal angle (f) (Brink et al. 1996).

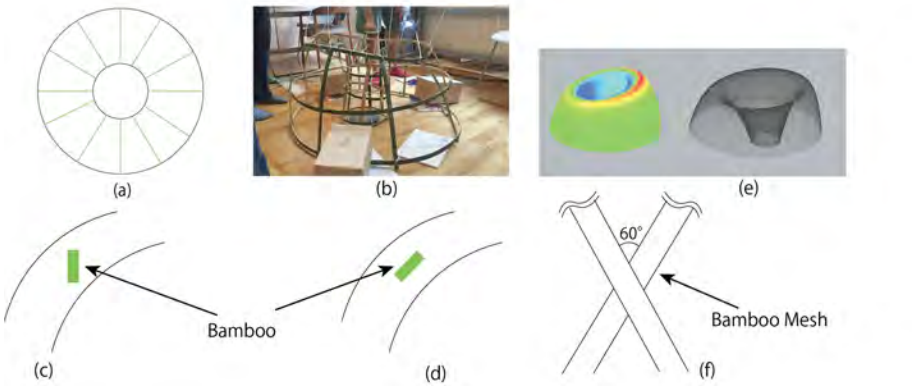


Figure 5. Design of donut-shaped bamboo geometry.

3.2. LASER RANGE FINDER

In order to check the errors, a laser rangefinder is deployed to conduct measurement accurately throughout construction and feedback is given to the parametric model. The measured data is stored in an Excel file which would be loaded to the 3D modeling software. As the geometry is a curved surface, a laser rangefinder is chosen among other options for measuring the shape. If the geometry is a cube, for example, the more points have to be measured. Plus, some points are unmeasurable from a certain spot. On the other hand, a curved surface requires fewer points to be measured. Besides, in this concrete shell, no points is hidden by itself. Thus, using laser rangefinder is reasonable.

3.3. AUGMENTED REALITY

AR technology is used for guiding the mesh geometry when the bamboos are woven. Unity and Vuforia are used. AR marker is made with Vuforia. In Unity, the marker and 3D models are related and checked through Android tablet during the construction process. AR played a role as a balancer of the mesh direction. Even if the actual shape deviates from the originally designed model, it can guide the direction of the mesh.

4. Experiments

In this section, two experiments are shown below. One is done without proposed system, other is done with proposed system.

4.1. EXPERIMENT 1

The construction period is 6 days. The total number of construction workers is 4 people. The location is within the premises of Keio University, Kanagawa, Japan, not on the island (figure 6). There was also a secondary purpose to determine the construction procedure of the concrete shell to be built for Experiment 2. First, the position of foundations of building was determined with a laser rangefinder fitting to the digital 3D model. After that, the building was built not using digital technology but just by hand manually. The bamboo weaving phase was completed as scheduled. However, there was a problem with the number of supports and the height of edge arch. The number of supports was not considered in the construction process of Experiment 1. Moreover, a serious problem arose as an error on the edge of the arch was found.The edge arch was about 10cm lower than the 3D model.As the shell became lower by 10 cm, it seems that the shell approached a planer shape from the curved shape, and the weight of the concrete was directly applied in the vertical direction and buckled (figure 7) (Terai et al. 2010).



Figure 6. Construction process & Buckling.

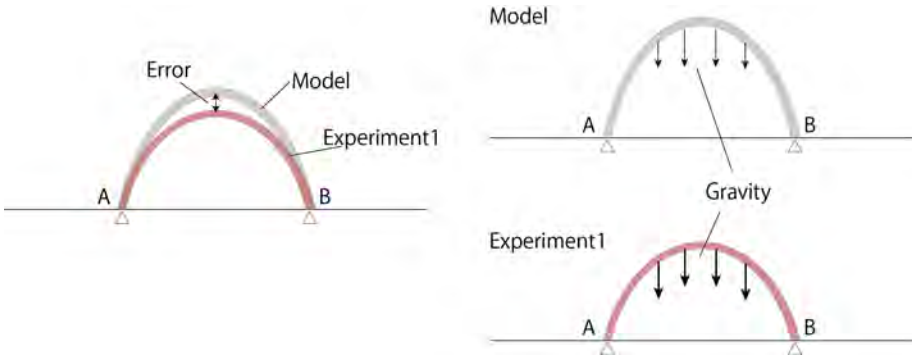


Figure 7. Error of edge arch.

4.2. EXPERIMENT 2

In experiment 2, a post-adaptability system was adopted in addition to the pre-adaptability 3D model of Experiment 1. The system has the ability to check up building information during construction. The Construction period was from 8/4 to 8/14, for a total of 12 days, the location was Kuchinoerabu island. The construction process was divided into two terms. The number of construction workers was three for the first term, four for the second term and eight for casting concrete. The size of the bamboo reinforced concrete shell was designed to be twice as large as Experiment 1.

4.2.1. First Term

AR shows the position of each part in the target premise. The number of bamboo calculated in 3D model analysis was 113, with diameters from 4.0 to 5.0 cm. Each bamboo was cut into four in order to make use of the characteristics of bamboo. It also approached the streak width (2.0 - 3.0 cm) of the geometry of the shell set on the 3D model. The position of the foundation was done by using a laser rangefinder.Bamboos were sorted out matching with the edge arch. Round bamboos were adopted in Experiment 1; sometimes there was no well-matched bamboo. On the 3D model the bamboo's thickness of the edge was set to 5 ˜ 6 cm. Therefore, in Experiment 2, the divided bamboos were overlapped to make their thickness closer to the 3D model edge arch.Concrete of the foundation part was cast. The degree of Z axis direction (height direction) deviation of the constructed edge arch from that on the digital model was measured with a laser rangefinder (figure 8). As a result, the edge actually constructed was about 5 cm lower. It was ½ degree of the error at Experiment 1, and the error can be amended by increasing the number of supports to support the shell at construction, we considered it within the allowable range.



Figure 8. First term construction process.

4.2.2. Second Term

When building bamboo strings, AR was used as mesh guidance. The position of the edge support was measured with a laser range finder. Wire mesh fastened concrete to prevent concrete falling when casting concrete. Wire mesh was kept open with a gap of about 2 cm. Supports building was divided into two stages so as not to interfere with the work of assembling bamboo and the work of fastening the wire mesh. The support of the first step (until finishing and attaching the wire mesh to the bamboo shell) would be simple. Increase support in the second step (when bamboo shell concrete is cast). Cast concrete and dry it.The composition of concrete was 1 portion of cement, 2 portions of sand, and 0.3 portion of water. In addition, the amount of concrete was calculated based on the 3D model analysis and optimized to reduced weight on the shell. The thickness of shell on the digital model was 50mm, the actual constructed one varies from 50mm 70mm in different areas. Its curvature shape error was reduced. It passed the load vector test. One month after casting concrete, the load vector test of 150 kg weight on the top of shell was tested again; the intensity of shell structure was checked (figure 9). Now the structure is exposed as permanence experiment.



Figure 9. Second term construction process.

5. Conclusion and Prospect

In conclusion, towards the idea of 'Digital Construction', one of the useful benefits of digital technology in onsite construction is increased adaptability. Under this hypothesis, the result of Experiment 1 clearly demonstrates failure in the collapse caused by 'buckling'. Here, the proposed system was not used, so the assumed reasons of failure can be seen as the hypothesis of this system. That is the many site circumstances were not reflected in the design. On the other hand, in Experiment 2, the information (here the materialized geometry) is continuously taken from the site and updated to the digital model by using the proposed system. Manual, low-skill requiring shell structure construction is made possible by the system. (structural strength to be examined). While, as byproduct of this method, the allowance would be other key aspect of parametric modeling which the designer / constructor would work together using this system. In another word, the allowance implies a number of possibilities within a tolerable range. Precisely speaking, if the margin of error is properly set, the model (geometry in this case) can move. The implication of this project is that there are two sets of keywords for digital construction in remote locations (figure 10). One is about parts quality, unique parts instead of standardized-product. The other is about the use of a guiding system, from primitive usage like answering predetermined quests such as jigsaw puzzle, to much more advanced usage like reacting to ad-hoc conditional change, car navigation system is an example.

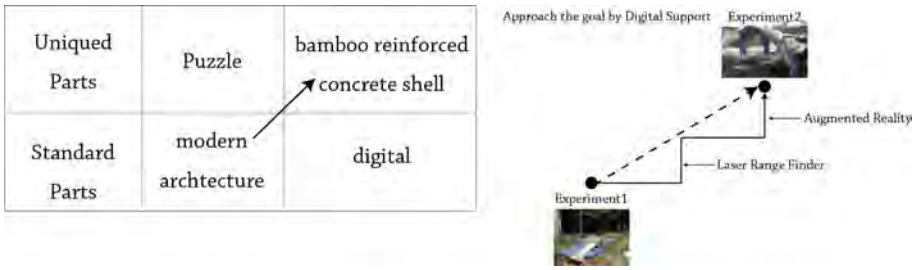


Figure 10. The adaptability of digital technology increases the possibility of digital construction.

Currently, the research is being conducted to attempt making those shell structure suitable for human habitation. Hence, the required architectural performance (structural strength for practice, environmental performance etc.), and architectural functions (toilet, kitchen, bedroom, living room etc) has to be pre-determined as objectives. Especially in architectural scale, the mean to divide inner space and outdoor space is yet to be studied, the notion of a semi-outdoor space is also attractive, as called Engawa in traditional Japanese intermediate space. On the other hand, on an urban scale, this proposal may have novel potential. That is how multiple shells can make grouping on site and it must be reviewed from the social perspective, because this project is ongoing at the volcanic island.

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DOUBLE-CURVED FORM APPROXIMATION WITH IDENTICAL DISCRETE PANEL GEOMETRIES

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Abstract. To reduce the costs of manufacturing multiple moulds for double-curved facade construction, this research suggests a method of approximating the desired envelope with identically formed panel geometries. The panels can then be fabricated by only using two double-curved moulds. In a second step, individual segments are cut out of the identical base geometries. The method has been successfully tested with the construction of a prototype. The result is an intricately textured free-form geometry. The installation was built at a reasonable cost compared to other ways of fabricating double-curved geometry. The strength of the panels was utilised as the sole structural system of the prototype.

Keywords. Architecture; façade; double-curvature; discrete components; panelisation.

1. Introduction

The main challenge in the construction of double-curved facade geometry is the cost of manufacturing individual panels (figure 1). Except in few cases, a seemingly double-curved facade is rarely actually constructed double-curved; more often it is rationalised into flat or single-curved elements that approximate the intended double-curvature (Ceccato 2012). The economic challenge lies in the costs of manufacturing moulds against which the façade panels are formed. For the fabrication of panels from various materials, such as aluminium, glass, fibre concrete or polymers, usually a separate mould needs to be manufactured for each panel (Lee & Kim 2012). Alternatives such as Multi-Point Forming offer savings but are still relatively costly (Lee & Kim 2012).

In order to allow for an affordable manufacturing of complex form, architects have proposed geometries that are based on a limited amount of identical discrete components (Sanchez 2016; Retsin & Jiménez García 2016). While this may provide an answer to the economic issues of the construction, it very often leads to geometric systems that appear pixelated rather than flowing.



Figure 1. Sahya.

We therefore propose a method of double-curved façade construction that utilises identical discrete panels during the forming process, which are then trimmed in order to align to the desired free-form envelope. The method has been tested with a prototype and was evaluated for its aesthetic and economic performance. It was shown to cost significantly less than a fully double-curved construction while resulting in a dynamically flowing, textured geometry.

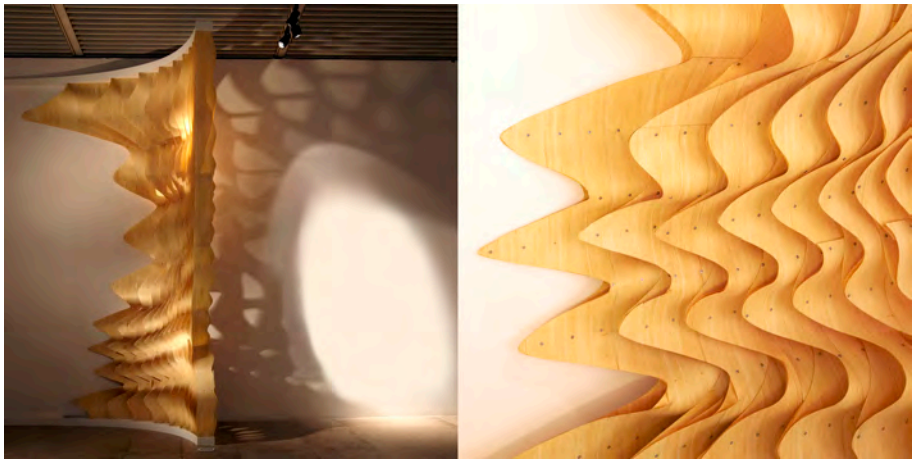


Figure 2. Anisotropia, at the National Museum of China, Beijing.

2. Related Work

Previous research by the authors utilised individually trimmed, single-curved panels in order to approximate a double-curved geometry (Klemmt 2012). The installation Anisotropia used bamboo veneer strips hung in tension from the ceiling. Similar to the proposed system, the bamboo panels were trimmed in order to align

to the desired free-form envelope geometry. The result was a dynamically flowing, textured geometry with similarities to the prototype of this research, however with all panels extruded along the same axis (figure 2). The methodology proposed in this paper therefore is a 3-dimensional generalisation of the previous work.

Aesthetically, some projects of Justin Diles and Neri Oxman have similarities to the constructed prototype, especially due to the free-form geometries in contrasting black and white colours they are based on. Eigenforms by Justin Diles uses double-curved panels to construct an indoor pavilion (Diles 2014). The sculptures Minotaur and Leviathan 2 by Neri Oxman are manufactured using 3d printing (Oxman et al. 2012).



Figure 3. Pattern generation.

3. Proposed Panelisation System

We propose a system similar to that of our previous research (Klemmt 2012) in order to approximate a desired envelope geometry, which in this case uses discrete panels that are double-curved in two repetitive shapes, rather than being single-curved as in the previous work. The panel fabrication therefore uses only two moulds so that the costs of mould fabrication can be minimised. The panels are then CNC-cut to custom shapes in order to align to the overall double-curved envelope geometry and to generate architectural detail and complexity at the same time (figure 3).

The system is based on the desired free-form envelope geometry and on the geometry of the repetitive discrete panels. The panels need to be able to connect laterally to their neighbours. In the arrangement that has been used for the prototype the panels connect to the adjacent panels in a tangential manner, which results in a seemingly continuous surface morphology within each layer of the system. The adjacent panels are arranged in a shifted grid with curved rather than straight edges. In the third direction the panels connect to the neighbouring surface layers also in a tangential manner, with the layers touching along the length of a curve.

The panels are then repeated in their arrangement to fully fill the desired envelope geometry. Any panel that intersects with the envelope geometry is trimmed along the intersection curve. If all panels connect in tangential manners and if the envelope geometry is free-form without any sharp edges, the resulting morphology will likewise be free-form without any sharp edges.

The connection hardware between panels can use various details depending on the materials used and on the design intent. The adjacent panels within the same surface layer can be designed to overlap.

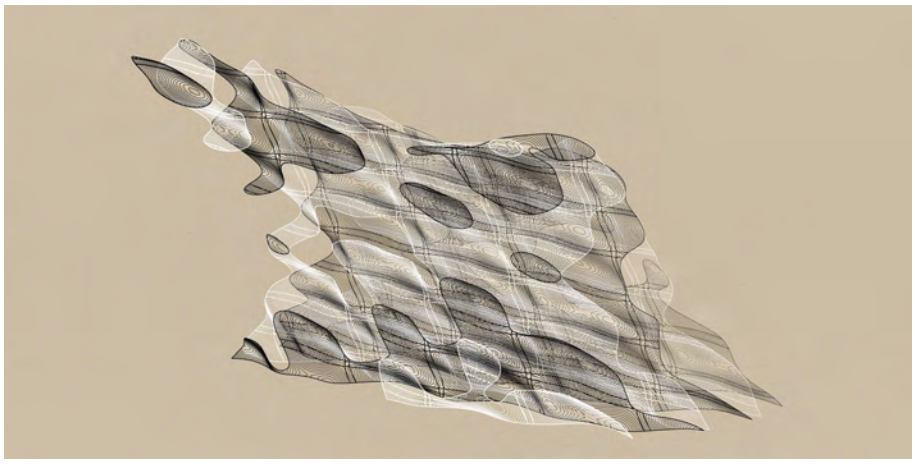


Figure 4. Prototype Design.

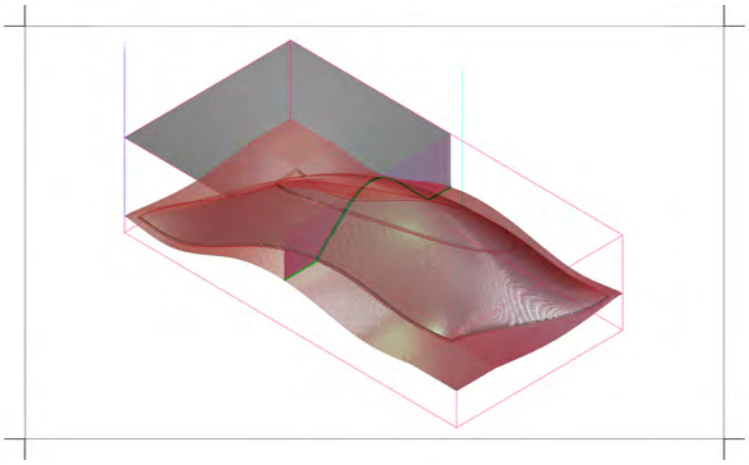


Figure 5. Toolpath for the moulds.

4. Prototype

The proposed methodology was tested with the construction of a prototype, titled Sahya, at the Venice Biennale 2016. The overall geometry was designed as a double-curved volume with dimensions of 3m x 1.5m and 1.5m height (figure 4). The resulting assembly is based on fully double-curved panels and on curved separations between those. The repetitive arrangement of the individual components becomes imperceptible against the overall geometry and its patternisation. The panels form the visible surface of the prototype while at the same time act as the structural system of the self-supporting installation. The fabrication of the panels for the prototype was carried out in three stages:

- manufacturing of the moulds in aluminium and wood
- vacuum forming of Acrylonitrile butadiene styrene (ABS) sheets
- CNC-cutting of the individual panels

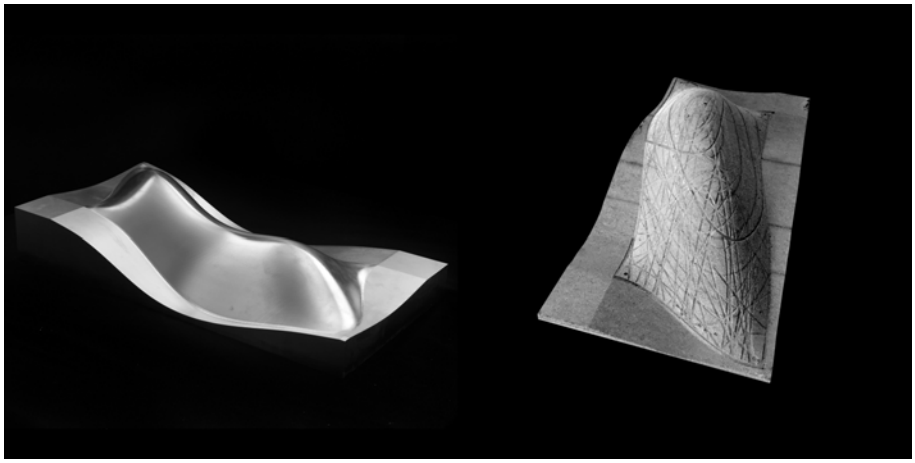


Figure 6. Aluminium mould and the wood mould as base for the CNC-cutting.

4.1. MANUFACTURING OF THE MOULDS

Two sets of moulds were made for fabrication. The first set of moulds, one for each panel type, were made using solid aluminium. Two blocks of aluminium of size 300x600 mm and 150 mm thick were CNC-cut into the geometry of the two panel types. 0.1 mm holes were manually drilled into the moulds for air extraction during the vacuum forming process (figures 5 & 6).

The maximum curvature deviation of the double-curved mould surface is 150 mm. Owing to the vacuum formed panel's relative thinness of 4mm, additional CNC moulds in wood had to be manufactured to hold the panels in place during CNC cutting. Like the aluminium mould, the wooden moulds were re-usable and allowed for precise cutting. Six layers of 25 mm thick MDF were laminated to create two solid blocks of 300 x 600 and 150 mm thick, which were then CNC-cut into the geometry of the two panel types (figure 6).

4.2. VACUUM FORMING OF ABS SHEETS

The ABS sheets were made to order from ABS pellets. The custom order was made to achieve equal glossiness in finish on both sides of the panel as typically, ABS sheets available are glossy on one side only. 150 kg of ABS pellets were formed into 150 sheets of ABS of size 400x700 mm and 4 mm thickness, in both black and white colours. The weight of each sheet was 1 kg. An extra margin of 50 mm on all sides served as a grip for the vacuum forming.

The panels were heated to 120 degrees for one minute to achieve plasticity in the ABS and subsequently vacuum-formed over the aluminium moulds. The panels were allowed to cool for 3 minutes over the aluminium mould before detachment to avoid shrinkage. Both aluminium moulds were used to cast panels in white and black colours producing four types of panels: Type 1 in black and white and Type 2 in black and white.

4.3. CNC CUTTING OF INDIVIDUAL PARTS

The cast ABS plastic panels were secured to the wooden mould with clamps and aligned to the CNC machine using registration points. The custom profile of each panel was cut and numbered based on the roll-out drawing. Wherever possible, more than one piece could also be cut using the same panel if the geometry of the cut lines of the two profile had no interference. A total of 200 panels were cut for the two mould geometries with two colour variations. In addition, a minimum of three and a maximum of eight 4.2 mm diameter holes were drilled in each panel to allow for fixing (figure 7).



Figure 7. 3d Cutting Schedule.

4.4. DETAILING

The panels were fixed to each other in layers. Each layer contained panels from both moulds but always the same colour to produce alternating layers of black and white panels. Built ground up, alternating layers of black and white panels were place and bolted together with pre-cut threaded rods with custom-made panel-coloured hexagon cap nuts, separated by EPDM gaskets.

5. Evaluation

5.1. AESTHETICS

The panelisation methodology results in a very intricate free-form aesthetic. The different curved layers in contrasting colours result in a flowing geometric overlay against which the repetitive arrangement of the panels disappears (figures 8 & 9). The proposed method does not result in a geometry that follows the desired envelope very closely but only ever actually touches it at the intersection curves with the panel geometry. It does manage to avoid any flat or single-curved geometry and any straight edges or joints. In comparison to the projects by Sanchez or Retsin and Jiménez García that utilise identical discrete components, the proposed method uses identically formed but individually cut discrete components. This allows for a much more dynamic aesthetic than the often pixelated morphologies that result from using identical components (Sanchez 2016; Retsin & Jiménez García 2016).



Figure 8. Sahya.

An aesthetic issue of traditional double-curved façade construction is the necessity to panelise the façade, which very often is done along straight lines for cost reasons and in order to optimize material usage (Ceccato 2012). The straight joint lines may in many cases be counterproductive to the creation of the dynamic that the curved envelope geometry may wish to achieve. In the proposed method, the curved panel edges come at hardly any extra cost. Any secondary structure along the curved edges or other relating architectural components will follow the identical curvature at every edge and can accordingly be mass produced.

As applied in the prototype with alternating layers in black and white, the geometric aesthetic appears to have similarities with Eigenforms of Justin Diles or Minotaur and Leviathan 2 of Neri Oxman (Diles 2014; Oxman et al. 2012).

However, a single-colour application is likely to appear much more homogeneous. While the aesthetic is different and more textured than constructing the desired envelope as a single, double-curved surface, this specific aesthetic may be suitable for many projects.



Figure 9. Sahya, detail.

5.2. COSTS

Four methods of manufacturing the desired envelope geometry were explored to develop a relative cost comparison table. In addition to the proposed system of fabrication using a pair of identical double-curved panels, costs for fabricating the geometry using flat panels, Multi-Point Forming and double-curved single surface panels were compared. Fabricating the geometry using flat panels requires the triangulation and rationalisation of the form. The product of the surface area of the geometry and the cost of panel per square meter were used to determine approximated flat panel costs at EUR 400 in 4 mm thick ABS plastic.

The production of the prototype using double curved, single surface panels requires the rationalisation of the geometry into 80 panels. The cost of raw material, moulds, 3d forming and panel cutting was calculated based on the same costs as the identical double-curved panels of the constructed prototype.

The relatively new technology of Multi-Point Forming has been applied to aluminium façade panels. A set of movable pistons is set to the desired geometry from above and below the sheet, which is then pressed against it (Lee & Kim 2012). Multi-Point Forming can be used on heated polymer sheets, however, care must be taken that the pistons do not leave individual marks on the material. The costs for this have been estimated based on research by Lee and Kim (Lee & Kim 2012).

Any costs towards packaging, transportation and on-site assembly have been excluded from the cost comparison table. However, the proposed system allows for panels to be stacked, so that the complete set of elements for the prototype could

be transported in two standard suitcases. The costs and estimated costs in table 1 show that the proposed methodology is significantly cheaper than a construction of the geometry as a single double-curved and panelised surface. However, the methodology is still more expensive than approximating the geometry with flat panels.

In comparison, the construction systems used for the example by Diles utilises individually cut moulds as is therefore commercially not feasible (Diles 2014). The example by Oxman was 3d printed and a commercially feasible 3d printing technology for similar large scale applications is yet to be developed.

Table 1. Cost Comparison for different Construction Methodologies.

	Approximated Flat Panels 800 panels 20 m² material	**Double-Curved Single Surface** 80 panels 32 m² material 80 moulds	**Multi-Point Forming** 80 panels 32 m² material multi-point press	**Identical Double-Curved Panels** 200 panels 80 m² material 2 moulds
Raw Material	€ 250	€ 400	€ 400	€ 1,000
Alu. Moulds	-	-	-	€ 2,350
Wood Moulds	-	€ 48,000	-	€ 1,750
3d Forming	-	€ 480	€ 6,400	€ 1,200
Panel Cutting	€ 800	€ 400	€ 1,200	€ 1,000
TOTAL	**€ 1,050**	**€ 49,280**	**€ 8,000**	**€ 7,300**

5.3. STRUCTURE

It was found that the panel assembly was able to withstand a significant load. At the scale and the dimensions at which the prototype was constructed it easily formed a self-supporting structural system. Because of their double-curvature, the panels had a significant inner strength.

Architectural large-scale aluminium panels are expected to perform similarly in regards to their structure. It is expected that, depending on the scale and material thickness, stiffeners may not be required. Depending on the main structure of a building, the secondary structure could possibly be reduced to local connections at each fixing point. The possibilities of the panels as the sole structural system of a façade or complete small-scale building would have to be investigated in detail for the specific project. The proposed method can easily provide building enclosure, insulation and waterproofing along the panels within one surface layer. This innermost layer of the façade could directly be constructed from insulated double-curved panels.

6. Conclusions and Future Work

The proposed methodology for the construction of double-curved volumes based on identically double-curved panels has proven reasonably affordable. The system has shown to have intricate aesthetic qualities that have not been built yet at a larger scale at a commercially affordable cost. The methodology and design aesthetic appear very suitable for an application as building scale aluminium façade system (figure 10).

The prototype sets out new directions to be explored: The system can be tested using aluminium instead of ABS plastic and suitable detailing needs to be developed to realise the system as a building facade. The multiple layering of the tiling systems could be developed as a passive thermal control system in the form of a self-shading facade or to channel air to regulate temperature around the building envelope. Due to the successful structural behaviour of the prototype, the system should be explored as a self-supporting structure in form of a larger pavilion.



Figure 10. Sahya.

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SMARTNODES PAVILION

Towards Custom-optimized Nodes Applications in Construction

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Abstract. Recent developments in Additive Manufacturing are creating possibilities to make not only rapid prototypes, but directly manufactured customised components. This paper investigates the potential for combining standard building materials with customised nodes that are individually optimised in response to local load conditions in non-standard, irregular, or doubly curved frame structures. This research iteration uses as a vehicle for investigation the SmartNodes Pavilion, a temporary structure with 3D printed nodes built for the 2015 Bi-City Biennale of Urbanism/Architecture in Hong Kong. The pavilion is the most recent staged output of the SmartNodes Project. It builds on the findings in earlier iterations by introducing topologically constrained node forms that marry the principals of the evolved optimised node shape with topological constraints imposed to meet the printing challenges. The 4m high canopy scale prototype structure in this early design research iteration represents the node forms using plastic Fused Deposition Modelling (FDM).

Keywords. Digital Fabrication; Additive Manufacturing; File to Factory; Design Optimisation; 3D printing for construction.

1. Introduction

Designing with freeform surfaces in architecture frequently leads to structural frames with members meeting in irregular junctions in unpredictable numbers at unpractical angles. Dealing with such nodes can involve, for instance, ubiquitous spherical geometry with custom welded plates or fixings. Such customisable nodes are expensive, time consuming to produce, and wasteful of material to accommodate every possible configuration. This adds significantly to the weight of individual nodes relative to their essential structural performance, which in turn adds

weight to the overall structure. The question arises: could a freeform structure be made primarily from standard construction materials, with every unique node (1) individually optimised for its structural performance in its specific location, (2) shaped to accommodate the irregular confluence of structural members, and (3) be 3D printed in metal, taking advantage of the mass customisation opportunities of that technology?



Figure 1. SmartNodes Pavilion at 2015 Urbanism/ Architecture BiCity Biennale, Hong Kong.

New means of advanced manufacturing offer potential for a historical shift from the mass-production of repetitive parts, to mass-customization on an industrial scale. Mass customisation promises the combination of automation, efficiency, and design freedom. This paradigm, first proposed by Davis (1987), transcends the principles of mass production and extends the notion of modularity to provide distinctive performance characteristics. Advanced manufacturing technology allows for building components to be customised to local conditions, based on aspects of systems of design and delivery (Exner et al. 2016).

An earlier iteration in this research project started to investigate this opportunity through applying Bidirectional Evolutionary Structural Optimisation (BESO) (Huang & Xie 2010). This technique can minimize material volume and weight in a part. This research iteration involved the design and construction of a scaled pavilion structure with printing of full-size metal nodes (Crolla & Williams 2015) (figure 2). The principal issues highlighted through these included challenges in printing with excess material required for support during the process including a) problematic heat build-up in the printing process, b) excess support material that was labour intensive to remove after printing.



Figure 2. 3D Printed stainless steel node, prototyped at full-scale using Selective Laser Melting (SLM) technology.

Here we report on a second iteration of the research. The research goal remains to develop design methodologies that allow the construction of geometrically unique freeform architecture, primarily built from standard available means and requiring limited onsite skill, through the integration of all complexity into individually customised and 3D printed nodes. This second iteration focusses on testing practical applicability through a full-scale pavilion project and explores the opportunities for topologically constrained node forms that marry principles of evolved nodes with geometrical constraints imposed to meet printing challenges. We introduced a fixed node topology for which minimal support material was required during the 3D printing process. Components of this topology were sized in response to key constraints in additive manufacturing, including the limitation of required printed geometry scaffolding during the applied Fused Deposition Modeling (FDM) process.

2. Pavilion Design

The SmartNodes Pavilion (figure 1 and 10) is a sculpture placed in the courtyard of the Hong Kong Heritage Discovery Centre in Kowloon Park. It operates as a shading device and sculptural feature for the public terrace. The structure consists of a single layered, treelike canopy that cantilevers out from a single central column. This column is anchored into a thin in-situ cast concrete slab that operates as ballast. The structure has a trefoil-like symmetrical topology that was freely stretched and deformed to create a more dynamic and natural looking result.

The SmartNodes research project seeks to identify and prototype a system which could be deployed in a range of scenarios. We focussed design and research on common the problem of customised node design and fabrication. Across the form of the pavilion, 39 unique nodes connect 183 linear beam elements which are unconstrained in the angles at which they meet. Three structural hierarchical axes respond to loading. Primary structural lines run from the bottom to the top pavilion edge and are split up into three parallel lines that are fixed into the same end nodes. Secondary structural axis are similarly split into three parallel lines, but commence halfway up the pavilion structure and run until the upper edge. Tertiary axis are kept as single lines. The splitting up of the axis into parallel members increases strength and permits easy fabric installation (see below). The number of

members joining into a single node ranges from five to eleven, resulting in a total of eight different node types.

By focussing design and fabrication primarily on the connecting node points, these smallest components of a framing system can be produced with relatively expensive digital fabrication techniques without resulting in much higher overall cost, as most volume and weight of the project remains composed of conventional materials. In the case of the SmartNodes Pavilion, these materials were standard aluminium tubes and a fabric membrane - parts which are cheap, can be adapted to local supply in each scenario, and can be assembled with limited onsite skill requirements. The specialist components, plastic 3D printed nodes, were manufactured overseas.

3. Structural Assessment

The SmartNodes Pavilion's structural model was fully 3D drawn in McNeel's Rhinoceros®, including all strut axis and node locations necessary to evaluate its structural performance in detail. The Karamba plugin for Grasshopper® was used within the Rhinoceros® software environment for simulation and analysis of different design iterations. Interactive experiments with the structural model as a virtual prototype allowed predicting the performance of the structure through simulation and iteratively improving the performance of the system. This process for on-going performance assessment based on a specified set of characteristics is referred to as virtual prototyping (Burry & Burry 2016). Based on the cross-section optimisation algorithm of the plug-in and the selected construction materials, the necessary dimensions for the struts of the pavilion were generated inside the parametric design environment (figure 3).

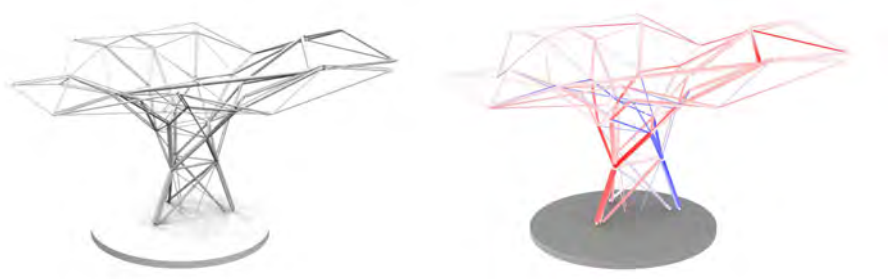


Figure 3. Structural Analysis using Karamba in Grasshopper®.

Using this parametric schema, different structural configurations could be easily tested and adjusted to improve the structural performance of the overall structure. All necessary loads were generated throughout the general structural analysis of the pavilion and no separate process was necessary to analyse the node topologies for structural performance.

As the pavilion was located in a heritage courtyard, the structural engineers considered site-specific wind loads. To simplify the structural evaluation based on

the focus towards the structural nodes, two design winds loads in x and y direction were applied.

For practical reasons related to local availability of material, strut diameters were limited to three types: two different sizes of struts were used, 20mm and 32mm, and one family was internally reinforced with steel stiffeners. These were necessary to handle high loads in areas where available diameters of aluminium rods would not suffice to resist buckling.

4. Node Development

Throughout the structure, eight different node types can be found that join different numbers of members. Fixed topologies were introduced for each of these types. In developing these typologies, the key goal was to improve the manufacturing process through minimising support material in printing, thereby reducing both time and 3D materials, all while keeping straightforward onsite assembly in mind.

4.1. NODE TOPOLOGY DESIGN

The printing process was limited by built-in software constraints put in place by the tool makers. Although these constraints could theoretically be circumvented by customization of the control software of the manufacturing hardware, that was deemed beyond the scope of this research project. Instead, rules of thumb, gradually defined through several study prints, were used to define most efficient node geometries. Factors such as node orientation in the printing bed and control of angles of overhang became dominant design criteria.

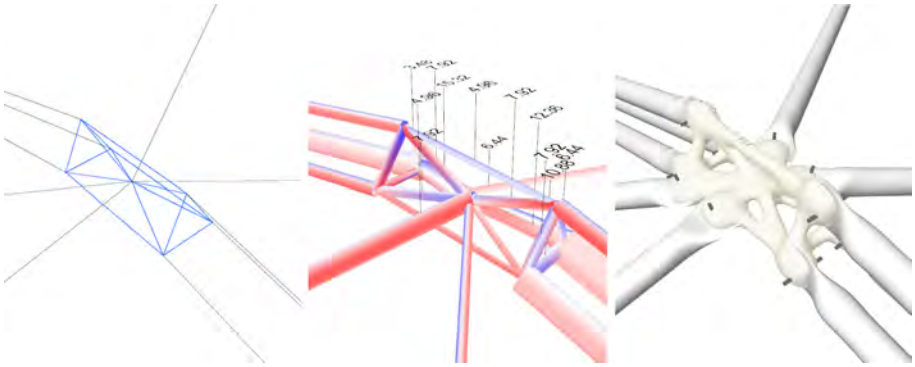


Figure 4. Node typology for Mesh Generation.

3D printed meshes were generated by procedural extraction using the 'Geometry Wrapper' function in Millipede, another structural analysis and optimisation plugin for McNeel's Rhinoceros® plugin Grasshopper®. This generates an equipotential mesh surface around defining input geometry. The input geometry used for the node surface generation consisted of the node topology axis lines and placeholder geometry in areas where connections with the aluminium members were placed (figure 4). For the member axis lines, different weightings were intuitively used for geometry at the top of the pavilion (lighter) and at its base

(heavier). For the connection slots with the aluminium pipes, an iteratively defined fixed weighting was used. To allow mechanical rod fixing, a screw hole was extracted from the mesh geometry prior to printing and the weighting was defined to produce sufficient mass for an effective load transfer without breaking.

The values used to define the equipotential mesh surface can easily be parametrically linked to printed material properties, resulting in thinner node geometry for metal prints and more chunky outcomes for plastic. Time and financial constraints of the projects, however, did not allow for this in this iteration.

4.2. NODE FABRICATION

The custom optimised node fabrication resulted in a range of 3D printed geometric expressions, generated based on local geometry and load condition and defined by the number of struts surrounding each node (figure 5).



Figure 5. Front and back view of three 3D printed plastic nodes.

In principle, any 3D printing material could be used as long as node geometries are developed in response to the material properties. Future iterations will focus on Selective Laser Melting (SLM), as this mode of fabrication seems to be most promising for application at construction scale, even if demands from the construction industry for their use in construction projects cannot yet be met with the present stage of technological development (Crolla & Williams 2015).

In this case, all nodes were printed on 'Fortus FDM' machines using an ABS filament (figure 6). A number of parameters affect required printing time:

- Material can be deposited in layer heights ranging from 0.15mm to 0.3mm. A lower height produces a finer surface finish and minor differences in strength.
- Strategies for printing the internal volumes of objects vary the density and quantities of material, with a 'solid' model being printed relatively slowly and alternative densities of lattice offering possible time improvements.
- Printing support material effects both the material volume and required time, with extrusion material changed for each layer during printing, affecting surface finish quality and strength of parts.

Amongst these relationships, trade-offs must be made to select a best fit for a specific project. In this case, strength - particularly tensile strength between printed layers - led us to opt for higher density and slower prints. Support material was minimised through the controlled pre-defined node topology without reducing surface quality.

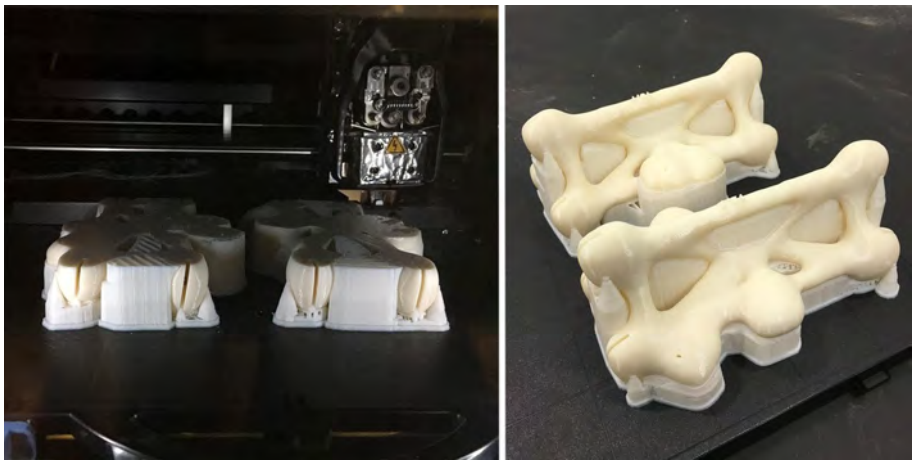


Figure 6. Nodes during and after the printing process.

5. Construction

In addition to the offsite printed nodes, all 183 aluminium members were prefabricated offsite. Following data spreadsheets extracted from the digital model, the tubes were manually labelled, cut to length, flattened at their ends, and pre-drilled for eventual onsite slotting into the nodes.

The fabric cladding was produced in three separate parts from a blue elastic fabric. Kangaroo, a particle-based physics simulation engine plugin for McNeel's Rhinoceros® plugin Grasshopper®, was used to define the flattened non-stretched geometry. A straightforward fixing detail was developed in which the membrane could be stretched in between the axis lines by having the aluminium members inserted into edge pockets closed by zippers.

The pavilion assembly required minimal technology (figure 7). Within a few days a team of three people with no construction experience managed to assemble all components and install the skin (figure 8).

A thin in-situ cast concrete slab was used as ballast for the structure. Protruding starter bars, bent to the correct angles were inserted and clamped into the aluminium tubes at the base to secure the connection with the canopy. Above the base, the aluminium pipes and structural nodes were assembled using standard screws.

6. Assessment and Future Research

Albeit fast, the rather intuitive 'Geometry Wrapper' does not produce fully optimised geometries. Following the completion of the pavilion, a randomly selected node design was revisited using the Scan&Solve(TM) plug-In for Rhinoceros. Its structural performance was simulated and a further volume reduction of the node geometry was done while respecting maximum loading capacity. This study exposed that a further volume reduction would have been possible of about 50% (figure 9).



Figure 7. Assembly.



Figure 8. Lycra skin detailing around various nodes.

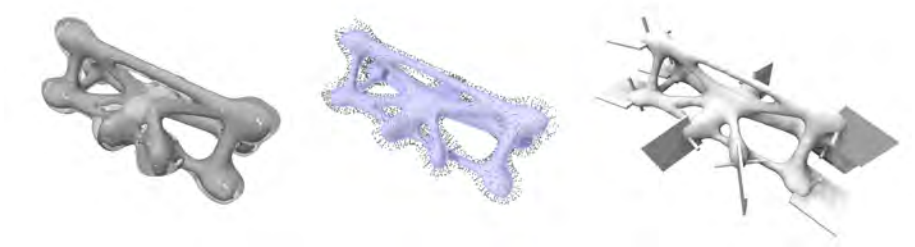


Figure 9. Comparing geometry of manufactured and simulated Node.

Alternatively, the cross-section optimisation algorithm of the Karamba plugIn for Grasshopper® could be used as an efficient method for structural evaluation and section optimisation of node components: it can generate weighting values for fixed node topology components defined using the 'Geometry Wrapper' function described here.

Although theoretically possible, further volume improvement would be difficult to realize in layered ABS plastic because of possible local defects occurring during the additive manufacturing process. Even if larger local defects, as occasionally observed in some of the nodes, could be avoided, the local properties and microstructure of the material may still vary significantly. Many conditions affect structural behaviour, including the specific machine used in production, materials, and their interaction with climate. To check calculated structural behaviour and adjust input parameters, a series of tests should be performed and weathered on-site. Such first-hand empirical tests are critical until industry standards further mature.



Figure 10. SmartNodes Pavilion by night.

7. Conclusion

This research investigated the use of a fixed-topology optimisation approach to mass-customized structural nodes to reduce the material needed for the additive manufacturing process. This has been prototyped through the design and fabrication of a pavilion structure at full-scale. This included customised nodes that incorporate geometric complexity and details for ease of assembly, allowing for straightforward on-site construction of freeform structures.

The results are significant in three respects: (1) the optimisation-based system for mass-customisation of structural nodes developed during the research indicated the potential for topological constraints in the optimisation process to develop a system of custom nodes that can be produced through 3D printing without gener-

ating excessive support material, (2) the construction process and procedure was successfully tested using the fabrication data generated from the parametric model, and (3) the whole system was tested under outdoor conditions, including significant wind load, during building occupation as part of a larger exhibition context. Future work will further investigate the application of this node system to full-scale metal printing.

Further optimisation of nodes will require (a) more detailed information on the structural behaviour of 3D printed materials and (b) further embedding of local structural engineering knowledge into the design team. However, designers will face significant challenges in assessing large quantities of such data and responding through design proposals. Heuristic and pragmatic responses are likely to be more readily adopted.

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- Overseas team: Nicholas Williams, Manuel Muehlbauer, Jane Burry (RMIT), Brendon McNiven and Reece McCorkindale (Arup Melbourne).

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Shape Studies

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GROWMORPH: BACTERIA GROWTH ALGORITHM AND DESIGN

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Abstract. GrowMorph is an ongoing research project that addresses the logic of bacterial cellular growth and its potential uses in architecture and design. While natural forms have always been an inspiration for human creativity, contemporary technology and scientific knowledge can allow us to advance the principle of biomimesis in striking new directions. By examining various patterns of bacterial growth, including their parametric logic, their use of responsive membranes and scaffolding structures, and their environmental fitness, this research creates new algorithmic design and construction models that can be applied through digital fabrication. Based on data from confocal microscopy, simulations were created using programming language Processing to model the environmental responses and morphology of the bacteria's growth. To demonstrate the utility of the results, the simulations created in this research were used to design an organically shaped pavilion and to suggest a new digital knitting process for material construction. The results from the study can inspire designers to make use of bacterial growth logic in their work, and provide them with practical tools for this purpose. Potential applications include novel designs for responsive surfaces, new fabrication processes, and unique spatial structures in future architectural work.

Keywords. Synthetic Biology; Architecture; Bio-fabrication; Bio-constructs; Design Computation.

1. Introduction

Architects have always looked to the natural world for inspiration, and today's algorithmic technology opens exciting new horizons for incorporating biological growth patterns into the realm of design and fabrication. Recent work in this area has only begun to explore the possibilities of using biological systems either as a

model for design algorithms (Duro-Royo et al. 2015) or as an actual component in fabrication processes (Araya, Zolotovsky, & Gidekel 2012). Organic processes are an ideal model for sustainable architecture, as evolution has produced brilliant arrangements that often produce little or no waste while remaining strong, durable, adaptable, and flexible (Discher, Janmey, & Wang 2005; Philp & Stoddart 1996; Vincent 2012). Our ability to model organic processes in architecture and construction is still in its infancy, as we have not yet even begun to approach the level of sophistication that is seen in the natural world (Benyus 1997; Oxman et al. 2012; Vincent 2012).

GrowMorph is a research project that advanced our knowledge in the area of bio-mimetic architectural design by analyzing the logic of bacterial cellular growth. By examining various patterns of bacterial growth, including their parametric logic, their use of responsive membranes and scaffolding structures, and their environmental fitness, this research creates new algorithmic design and construction models that can be applied through digital fabrication. This investigation stands at an interface between biological systems and architectural design, using computational techniques to simulate and model biological processes.

2. Nature-Inspired Morphogenesis

In the natural sciences, the term "morphogenesis" is used to describe how structures develop in geological formations and biological organisms. Recent decades have seen a growing interest among architectural designers in studying these natural processes as a way to inform human-created structures. Evolution has in many cases produced designs that are remarkably efficient in terms resource-use while remaining durable and resilient in variable environmental conditions (Reap, Baumeister, & Bras 2005; Vincent 2012; Vogel 1998). Contemporary design and construction technology offers exciting new opportunities to take advantage of strategies derived from the natural world. For example, Kreig and colleagues (2012) drew from biomechanical studies of the sea urchin's form to develop a new type of jointed structural system. Ortega and colleagues (2000) used the model of organic tissues to develop new materials that are "self-healing" and tolerant of structural faults.

One of the most exciting areas of development in nature-inspired morphogenesis includes projects that analyze natural growth and configuration/adaptation over time. Moving beyond static configurations for final design solutions, and enabled by advances in "soft" robotics and nano-engineering, these approaches seek to model the natural processes through which effective designs are achieved within a local environment. For example, Tibbits (2012) has made strides toward developing self-assembling, adaptive, and programmable materials for use in industrial construction applications. Raviv and colleagues (2014) have developed a similar approach to designing complex, self-evolving structures that vary over time in response to environmental interaction.

Bacterial cellulose structures are a fascinating model for this cutting-edge biomimetic design research. Industrial, scientific, and medical applications for artificially grown cellulose have already begun to emerge, and although this field

is still in its infancy engineers see a great potential due to the material's structural integrity, hydrophilic nature, and biodegradability (Fernandez et al. 2013; Mohite et al. 2014). The use of bacterial cellulose in industry has advanced our knowledge of its properties and encouraged forward-looking designers to examine the material both as a model for architectural strategies and as a potential fabrication component.

Araya, Zolotovsky, and Gidekel (2012) explored novel modes of design and fabrication by combining digital tools and technologies with living biological systems in a controlled environment to induce specific biological functions and material production processes. Derme, Mitterberger, and Di Tanna (2016) similarly developed bio-fabrication and scaffolding techniques to control the 3D membranes and morphologies of bacterial cellulose, envisioning an application in the field of bio-materials science, digital fabrication, and material-informed computational modeling.

While the aforementioned research is compelling, there is still much work to do in the analysis of bacterial growth algorithms if we are to fully understand the morphogenesis of these materials. By learning about the morphogenesis of bacterial structures, we can learn to better engineer these materials and eventually to produce fully synthetic analogues that follow similar patterns of adaptation and development. The current research analyzes the growth patterns of bacterial cellulose both as a basis for new manufacturing/fabrication technologies and as a model for synthetic self-forming adaptive systems.

3. Method

The GrowMorph project is focused on two particular types of bacteria, Acetobacters xylinus and Synechococcus elongatus. These bacteria were selected for study based on the extent of the already-existing empirical knowledge about their growth patterns and the relevance of that knowledge to potential design applications. Early modeling investigations for both types of bacteria in this project include the analysis of image Z-stacks (multiple cross-sections stacked vertically) produced through confocal microscopy, as well as a review of relevant biological literature about cellulose structure and growth. Based on this data, simulations were created using programming language Processing to model the parametric environment and morphology of the bacteria's growth. These models then were applied to design and fabrication processes. In more advanced modeling stages, the bacterial growth structures were reconstructed in 3D digital space, and physical models were designed and fabricated to illustrate the potential of this bacteria-based architectural logic.

3.1. ACETOBACTERS XYLINUS

The most abundant bacteria on earth, Acetobacter xylinus, are prolific producers of cellulose when grown in a sugar-rich medium. A single A. xylinus cell has multiple pores along its body through which chains of large sugar molecules are extracted. The use of cellulose produced by A. xylinus has received a great deal of attention as a more environmentally sound alternative to plant-derived cellulose

(for the production of paper, etc.), as well as for use in sophisticated biomedical applications (Helenius et al. 2006). In recent years researchers have begun to take an interest in the morphogenesis of A. xylinus under the view that controlling the bacteria's structural development will be crucial to its uses in tissue engineering (Sano et al. 2010).

3.2. SYNECHOCOCCUS ELONGATUS

Synechococcus elongatus is a photosynthetic, single-celled bacterium that is widespread in freshwater environments. It is rod-shaped and tends to lump together in small clusters (Perkins et al. 1981; Scanlan & West 2002; Waterbury et al. 1986). Results presented by (Koblížek et al. 2000) demonstrated that the speed and extent of the bacteria's aggregation is light-dependent. Under the right illumination, crystals of the Protein Structure Initiative (PSI) from Synechococcus elongatus form a hexagonal pattern.

4. Growth Analysis

The growth models developed in this study are based on observed bacterial behavior in the presence of light stimulation. The presence of light has been shown to activate genetic switching that, for the bacteria under study here, lead to specific patterns of cellulose production and therefore result in specific structural formations. The outcome of the process is structures that tend to open toward the light. Studying this process can help us to understand how biological assemblies adapt to environmental stimulation (Sano et al. 2010; Schubert et al. 1997; Zolotovsky 2012).

The model was constructed using programming language Processing. In the base form of this model a structural point (i.e. a cell) is programmed to select eight neighboring points in a random fashion. Four of the neighboring points are then eliminated based on distance (with the nearer points being retained). Two additional points are eliminated based on light intensity (with the darker points being eliminated). The remaining two structural points are linked by a mesh pattern based on the process of bacterial cellulose extrusion (figure 1).

One method for simulating the complex formations of the bacteria cellulose is to process the volumetric formation as a point cloud, and to evaluate the cloud in a single step. The cellulose-based mesh pattern used in this model is derived from the "marching cubes" algorithm developed by Lorensen and Cline (1987). Taken together, the eight neighboring points initially selected for consideration can be considered a "cube" surrounding the origin cell, and the growth pattern resulting from a combination of randomness and light simulation as a possible means of segmenting the cube. When the resulting form is combined with the results of the neighboring cubes (i.e., the cellulose extrusions of other cells), an overall mesh pattern emerges and expands over time (figure 2).

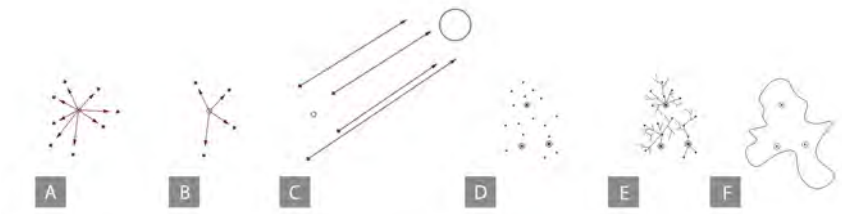


Figure 1. Bacterial growth behavior in the presence of light stimulation.

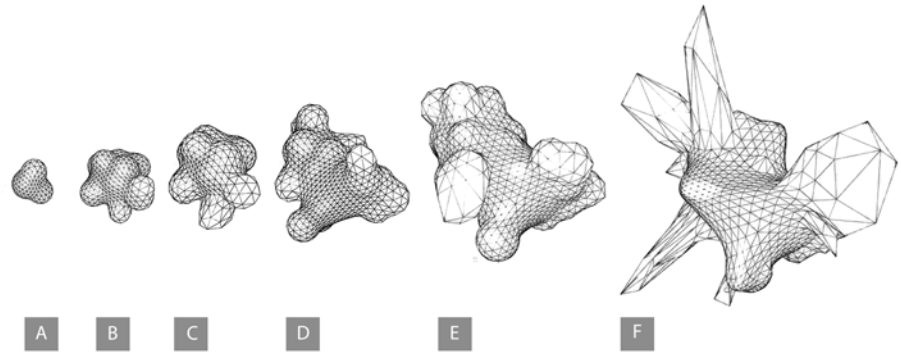


Figure 2. Mesh production based on the "marching cubes" algorithm: (a) cube numbering, and (b) triangulated cubes (Lorensen & Cline 1987).

4.1. PARAMETRIC CONDITION ONE

The parameters of the model were adjusted to investigate structural forms resulting from various kinds of observed bacterial behavior. The first parametric condition was the base model as described above. It simulates the behavior of A. xylinum bacteria when stimulated by a UV light source (Sano et al. 2010). As mentioned, each cell in the model is programmed to identify eight random nearby locations, eliminate six of the locations based on distance and light levels, and then extrude a mesh toward the remaining two points. One of the simulations resulting from this growth pattern is shown in figure 3.

4.2. PARAMETRIC CONDITION TWO

In this version of the model the growth pattern has been adjusted to describe the more cohesive and aggressive behavior of A. xylinum in conditions of abundant nutrients, again under the stimulation of a UV light source (Sano et al. 2010). The point selection under Parametric Condition Two is different from the previous algorithm. Each cell again selects eight random nearby locations. The algorithm then defines a polygon based on those locations, and the cell selects six new points

on the surface of the polygon, choosing the points on the surface that are closest to the origin cell. The process is repeated, defining a new, smaller polygon based on these six points, and then choosing the three nearest points on the new polygon. Of these three, the one with the lowest light intensity is discarded, and a mesh is extruded toward the other two points. The overall result of this process is that the chosen points tend to be much closer to the origin cell in comparison with the base model. One of the simulations resulting from this growth pattern is shown in figure 4.

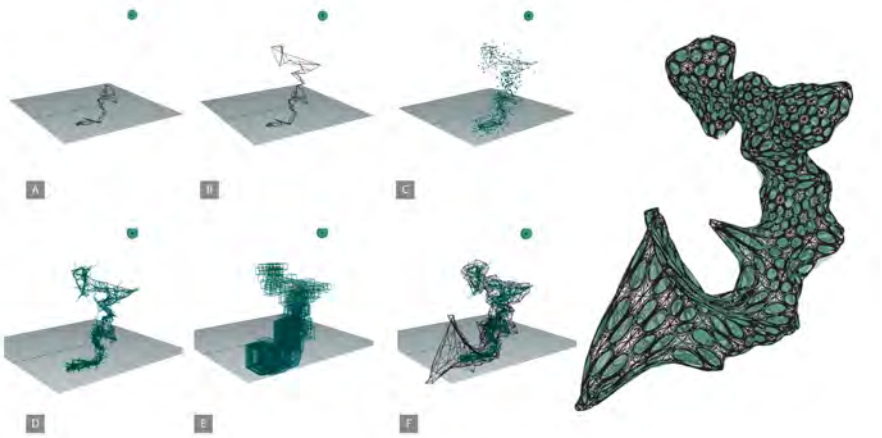


Figure 3. Simulation based on Parametric Condition One.



Figure 4. Simulation based on Parametric Condition Two.

4.3. PARAMETRIC CONDITION THREE

The third variation of the model is based on the symbiotic combination of Synechococcus elongatus with Acetobacter xylinum (Schubert et al. 1997). For this simulation we modified the base model by setting some random points to act as S.

elongatus. The notable feature of this addition is that the S. elongatus cells, under the influence of a UV light source, will form hexagonal space groups that interact with the surrounding A. xylinus growth patterns. One of the simulations resulting from this growth pattern is shown in figure 5.

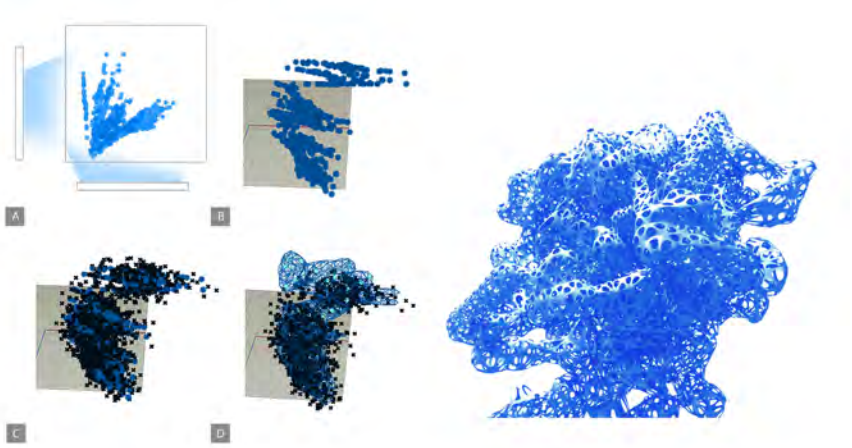


Figure 5. Simulation based on Parametric Condition Three.

5. Conclusions and Future Work

This project studied the growth patterns of Acetobacters xylinus and Synechococcus elongatus as a potential basis for computer-mediated architectural assemblies. The resulting simulations can be used as a means to understand the structural morphogenesis of bacterial cellulose for the purpose of developing controlled-growth applications, and it can also be analyzed in itself as a model for human-created environmentally responsive structures. Three versions of the simulation were created, incorporating different parametric conditions based on observed bacterial behavior (Sano et al. 2010; Schubert et al. 1997).

The results from the study can inspire designers to make use of bacterial growth logic in their work, and provide them with practical tools for this purpose. The 3D models produced in the research provide concrete examples of how bacterial growth logic can be used in design (figure 6), and can inspire new techniques of artificial material fabrication and assembly. The ultimate goal of abstracting biological growth patterns into code-driven models and tools is to gain new insights into how nature deals with physical dynamics, environmental parameters, and feedback within cell and tissue structures. The potential applications include novel designs for responsive surfaces, new fabrication processes, and unique spatial structures in future architectural work.

While this study presents a first step toward simulating bacterial cellulose growth in computer-aided design, there remains a tremendous amount of opportunity for analyzing organic assemblages. By linking the biological sciences to the

computational design process we can open significant new horizons for organically inspired design. In future work, we plan to design a plug-in for the Grasshopper software package that will allow users to explore various biological growth parameters. Producing actual edifices based on bacterial growth logic will help to inspire and further promote this design research area. Finally, future work may seek to apply organic growth models directly to digital fabrication, leading to new techniques in material production.

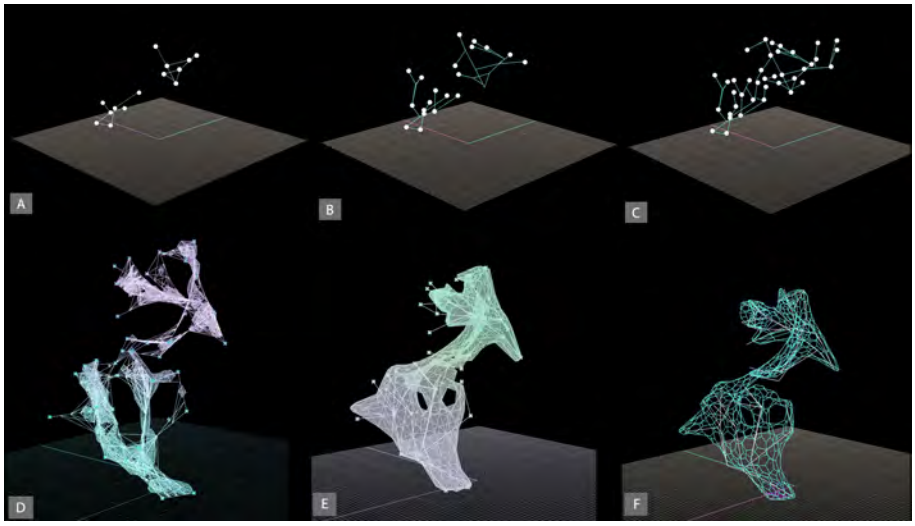


Figure 6. An organically shaped pavilion that was designed using the base model created in this study.

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TOPOLOGY-DRIVEN FORM-FINDING

Implementation of an Evolving Network Model for Extending Design Spaces in Dynamic Relaxation

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Abstract. This paper introduces a novel computational design methodology called topology-driven for the numerical form-finding of discrete networks and presents the essential building block for storing and processing information. Numerical form-finding focuses on computing the optimum geometric configuration of lightweight structures in which shape is the result of reciprocal dependencies between forces, material behaviors and structural performances. Among the design community, Dynamic Relaxation (DR) has gained in popularity given its capacity to support more flexible and interactive design spaces in form-finding. However, common implementations of networks models only focus on the interactive exploration of material and geometrical properties without further specification for topological dynamization. For facing this problematic, we propose an object-oriented approach to attach specific functionalities to particular pieces of data within the numerical schema. Here, we describe the implementation of a rule-based system for managing objects´ interactions in order to continuously track topological and geometrical changes. Based on this concept, larger design spaces can be developed for the interactive exploration of structural shapes.

Keywords. Topology-driven; Form-Finding; Dynamic Relaxation; Object Structures; Design Spaces.

1. Introduction

Recent advances in the integration of physics-based simulations within parametric modeling environments have given designers new ways for the exploration of forms beyond its pure geometrical description. This has facilitated the investigation of lightweight structures in which the final geometry cannot be predicted but need to be form-found. The field of Dynamic Methods which include Dynamic Relaxation and popular by-products like Particle-Spring Systems, has been frequently

used for this purpose in comparison to more mechanical accurate approaches like Stiffness Matrix Methods. This is mainly due to easiest implementations and reduced computational costs resulting on fastest convergences and increased interactivities. The underlying principle behind is finding a steady-state solution for a dynamic equilibrium problem by applying D´Alembert's principle of virtual work.

For initializing the algorithm, users are required to specify a set of initial conditions including a discretized model with specific boundary conditions and a set of parameters for controlling material and geometric properties. Major efforts for creating variation on form-found geometry are addressed through dynamic alterations of material and geometric parameters during algorithm´s runtime without further considerations for topological exploration. One reason is that topological alterations certainly tends to affect the stability of numerical solutions since a non-appropriate variation on connectivity could easily generate a system of unbalance forces that never converge. However, what makes topological modelling particularly interesting is the fact that designers can have larger design spaces to explore alternative solutions.

In this paper, we introduce fundamental concepts of the topology-driven approach for form-finding, and present the implementation of a rule-based flexible object structure for tracking topological and geometrical changes while guaranteeing a reliable connectivity of the system. Although this paper presents studies conducted exclusively on bending- and tensile form-active systems, and hybrid by-products, the topology-driven approach can be extended to the entire range of lightweight structures. The framework for the implementation is an in-house form-finding tool written in Java and tested during the Architectural Association Visiting School Madrid 2016. As a result, this research explicitly defines the topology-driven approach as the differentiation and activation of metric and non-metric design spaces for driving form-finding processes.

2. Elastically Deformable Structures

Elastically deformable structures mainly concern structures undergoing large deformations where equilibrium shapes are determine through interactions between form, material and forces. It is generally accepted that tensile form- and bending-active structures fall into this category. In both cases, it is important to consider the strategic use of elastic deformation as a mechanism to increase load bearing capacities. Moreover, tensile form- and bending active structures can be combined into a unique stiffer construct given common characteristics regarding flexibility, lightweight and pre-stress (Lienhard 2014). The term textile hybrid introduced by Lienhard et al. (2013b) is used to describe the integration of elastic beams elements within prestressed membranes.

In this context, most prominent contributions on the use of navigable metric spaces for form-finding relates to computational efforts for calibrating textile knitted membranes logics using dynamic methods (Ahlquist and Menges 2013; Schmeck and Gengnagel 2016) and the development of the contracting elastic cable approach based on FEM (Lienhard et al. 2014). In contrast, exploratory investigations in non-metric spaces are mainly carried by means of physical ex-

perimentation. For example, an increased flexibility in topological modelling has been reported with the use of analog models in projects like the CITA tower (Thomsen et al. 2015) and the ICD/ITKE M1 La Tour (Lienhard et al. 2013a). In both cases, a multistep modelling workflow has been proposed to solve the inherent geometrical, topological and material complexity of each system. In other words, topological data from physical models drives form-finding studies with dynamic methods whose results are in turn used for creating FEM models. Consequently, the entire computational design process is mainly based on analog computations of initial topological configurations.

3. Form-finding with Dynamic Relaxation

It is clear that the final geometric configuration of such structures cannot be predicted in advance since its shape depend on large deformations induced during the forming process. For form-finding, the Dynamic Relaxation (DR) method has gained in popularity given its capability to produce real-time feedbacks for the evaluation and analysis of material behaviors and structural performances in early design stages. DR consists on subdividing a continuous physical system into a finite set of discrete particles where masses are concentrated. Through an iterative process, the system of particles oscillates until finding a steady-state by balancing forces under the influence of damping. The algorithm requires the input of an initial topological configuration which is assumed to be intuitively solved before relaxation. While the algorithm is running, the designer can modify geometric parameters of the system until reaching a desirable solution (figure 1).

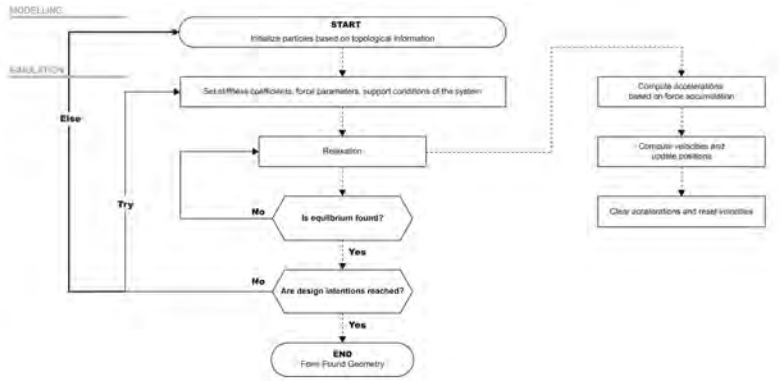


Figure 1. Classical workflow of the dynamic relaxation method.

The main issue is the necessity to break and re-initialize the algorithm for changing topological conditions when design intentions are not satisfied. This means that topological operations are carried on undeformed geometries where its consequences are hard to predict. Therefore, the integration of topological variation during algorithm´s runtime is a newly research topic in form-finding that has not been fully studied. At the moment, related efforts on topology modelling are conducted at CITA (Deleuran et al. 2016) based on Kangaroo Physics.

4. Metric and Non-metric Design Spaces

Topology-driven form-finding is an on-going research conducted at Institute of Building Structures and Structural Design (ITKE) regarding the development of a novel methodological approach for addressing the activation of metric and non-metric design spaces in form-finding processes. At this stage in the research, the problem of dynamizing the entire connectivity of the network during relaxation is primarily addressed. Using an object-oriented analysis, we create multi-dimensional model representation (i.e. graph, particle system, network topology, and network geometry) for approaching the dynamic control of metric and non-metric spaces during relaxation as a rule-based graph related problem. The main advantage of the object-oriented approach is attaching specific behaviors to data for describing more complex models. Therefore, this model allows us to define two concrete objects for implementation (i.e. particle and element) and organize different requirements inside them by means of detailed functionalities and data fields. To avoid confusions between the different dimensions of the model, we refer to graph as composed of nodes and links, network topology as composed of vertices and edges, network geometry as composed of points and lines, and physical system as composed of particles and elements. Each model refers to each other within different levels of abstraction and design spaces (figure 2).

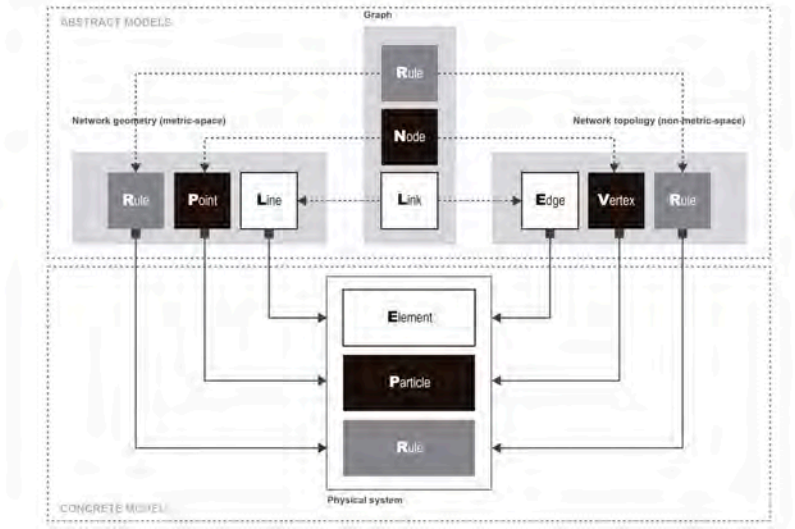


Figure 2. Interrelated terminology used within different levels of abstraction.

At graph's level, nodes need to be extended with attributes using a customized vocabulary. The vocabulary is built upon numerical combination of integer values describing all the possible states that a node could take within the graph. Among its most basic states, a node could be shared, activated, deactivated or isolated. Furthermore, nodes and links are labeled with key identifiers for facilitating searching operations. On this basis, a finite set of grammatical rules can be defined for controlling the entire connectivity of the graph (figure 3). Discrepancies on connec-

tivity are prevented by updating node´s sates with each transformation. Although grammatical rules might constraint design spaces, they are a transcendental condition for assuring stability and thus, convergence of numerical solutions.

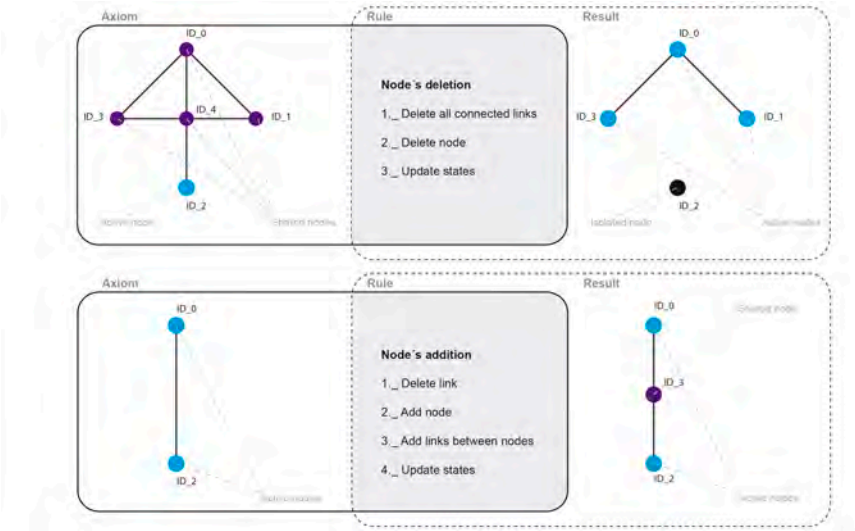


Figure 3. Examples of two basic grammatical rules for altering graph´s connectivity. Node´s colors are visual representations of its states.

5. Implementation

Numerical simulations in engineering sciences are typically programmed with simple and structured routines following the procedural paradigm. The reason for this is to make an efficient use of computational resources and thus, facilitate the production of detailed mechanical descriptions of structures. We must state that there is still some controversy concerning the increase of flexibility for computation since this characteristic inversely affects performance. The challenge of implementing numerical simulations within design workflows is then to finely adjust design flexibility and mechanical accuracy so that computational costs are reduced.

5.1. OBJECT-ORIENTED PROGRAMMING OF NUMERICAL METHODS

The topology-driven approach may be categorize as flexible approximation for adjusting and altering topological data under certain conditions within the numerical schema. Beyond pure performance-oriented implementations, this approach is rather difficult to program without the concepts of encapsulation, inheritance and open recursion of the Object-Oriented Paradigm (OOP). Through OOP concepts, we avoid the misuse of data and guarantee the creation of a hierarchical structure of classes with the ability to self-reference themselves.

For this stage of the research, the Java programming language was selected.

Among the main reasons, we mention portability and the wide range of standard classes of data structure included in the Java Class Library (JCL) that can be used for defining more complex structures. Additionally, the language has the great benefit of the built-in garbage collector allowing developers to not worry about the allocation and deallocation of objects in memory. This is a desirable characteristic for controlling memory leakage when complex routines regarding the dynamization of data are programmed.

5.2. A RULE-BASED OBJECT STRUCTURE

A small class taxonomy was designed to define objects´ interactions when performing tasks for modifying topological and geometrical data. Figure 4 shows a simple diagram that helps to visualize such class relationships. A *particle object* is the most fundamental building block containing essential information (i.e. position, velocity, acceleration and mass) for integrating Newton´s equations of motion. Moreover, an *element object* is a generic entity storing metric properties and system´s connectivity through particles identifiers. It also implements methods for computing accelerations on referenced particles through force-based formulations of finite elements like cables, beams or springs. Finally, a *rule object* contains fields for defining axioms and methods for altering *particle´s* and *element´s fields* on the basis of axiom´s evaluations.

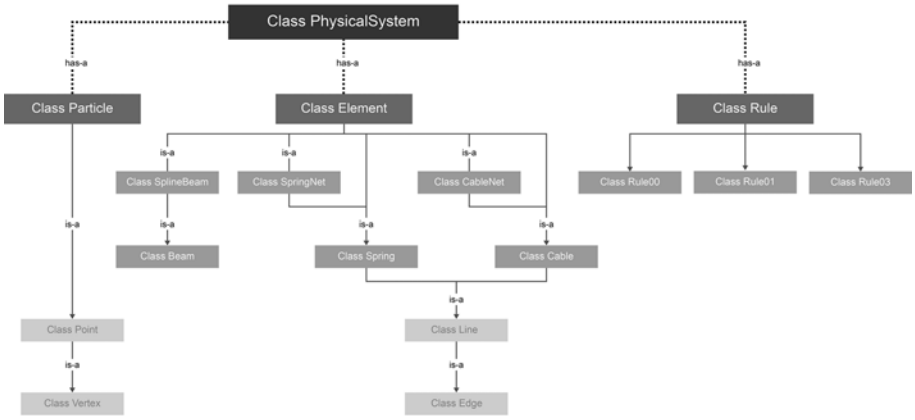


Figure 4. Class taxonomy.

We have mentioned before that states constitute the vocabulary from where axioms are defined. What is important here is that *particle´s states* are updated on the basis of a circular referential data with *elements*. That is, a *particle* stores all element´s identifiers referencing to this *particle* while at the same time, an *element* stores all particle´s identifiers used by this *elements*. As each *element* is modified, *particles´ states* and masses are updated. *Rule objects* use those states to trigger modifications. For example, a *particle* is suitable for deletion when its state is isolated. This means that the list of element´s identifiers is in blank. In a similar

manner, a *particle* can be added by creating an entirely new *element* referencing this *particle* or by regenerating an existing *element* into new *elements* that include references to all *particles*. In both cases, the final state of the new *particle* is shared. This rule-based approach guarantees the topological consistency and, thus, the numerical stability of the system.

Under this conditions, each *particle* is referenced within different *elements* irrespective to its sorting. *Particles* are stored asynchronously following an associative manner by mapping its position in computer´s memory with its unique key identifier. The HashMap class included in the JCL is used for this purpose. The main advantage of the HashMap class is time-complexity O(1) which means constant-time performance for basic operations. Such condition ensures similar performance for adding and deleting data, and better for searching in comparison to dynamic arrays normally used in numerical methods.

On the other hand, a HashTable is used to synchronously store *polymorphic element´s objects* (i.e. *element´s object* take the form of multiple finite elements formulations). Here, it is important to mention that a special variant of the *element class* is the *meta-element* which is used for describing specific sub-domains of interconnected *elements* as in the case of cable-nets, spring-nets or spline beams. The synchronous storage of *element´s objects* provides a way to keep track of the assembly sequence process during form-finding.

Finally, *Physical system* is the superclass containing no-inheritance relationship with *particle´s, element´s* and *rule´s objects*. In our strict definition, this superclass is an entity that organizes geometric and topological data while exhibiting specific behaviors based on grammatical rules. For simplicity, only one object of type *physical system* could exist in the simulation.

6. Case Study: AAVS Madrid Pavilion

The method was evaluated with the development of the shell-like bending-active part of the Architectural Association Visiting School (AAVS) pavilion Madrid 2016. This installation investigates how the aggregation of linear active- and passive- bending elements could be combined for shaping a morphological complex lightweight structure. The structure is divided in two parts (figure 5). The upper part which is an active assembly of GFRP rods manually pre-stressed under the limits of elastic deformations, and the bottom part being a passive assembly of robotically bent aluminum bars reaching plastic deformations. The aim of the active part was the development of a non-standard neither regular network of elastic rods where stiffening is the result of a progressive deformation induced by the aggregation and bundle of rods.

In this project, the active part was constructed using pultruded GFRP rods with solid cross sections diameters ranging from 5 to 20 mm. For studying how to introduce stiffness in the structure, computational models were used to evaluate the strategically aggregation of rods with different diameters, following a specific assembly sequence logic (figure 6). This was done in ElasticSpace, a custom-built form-finding software implementing the dynamic control of topology. The main advantage of this tool is the increased user-interactivity for modifying topologi-

cal assemblies during relaxation and improving the design while keeping track of minimal bending radii, strains and chronological modifications.

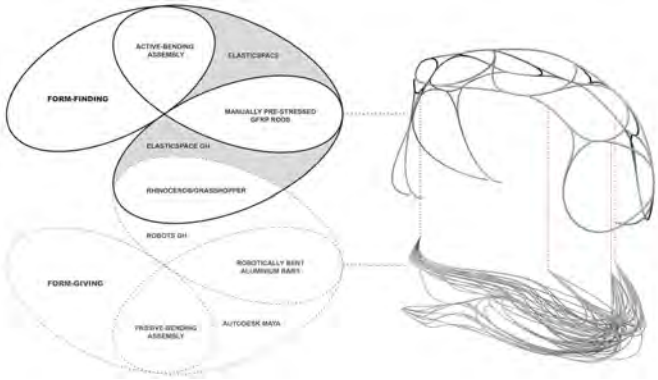


Figure 5. Design workflow of the project. The form-finding process of the bending-active part is carried with ElasticSpace.

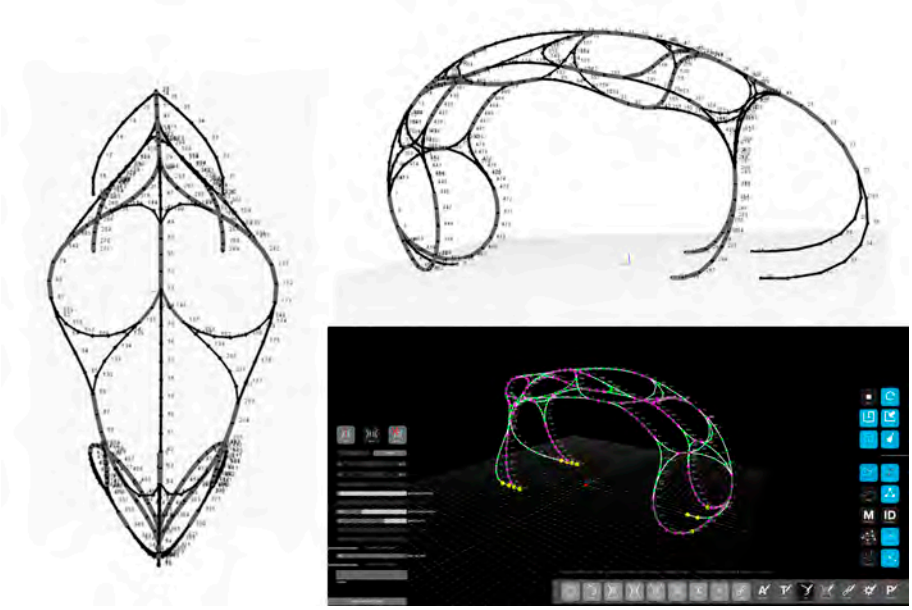


Figure 6. Computational exploration of bending-active assemblies with ElasticSpace.

This case study was built with dimension of 6m x 2m x 2.5m. The final structure was assembled on site and connected to the passive robotically fabricated structure (figure 7). While this project has validated the reliability of our implementation in terms of numerical stability, it has also proven the increased flexibility that the topology-driven approach provides in terms of design spaces. However,

one main criticism is the necessity for additional amounts of time-consuming steps for topological modelling and a reduction on interactivity with larger number of particles and elements.

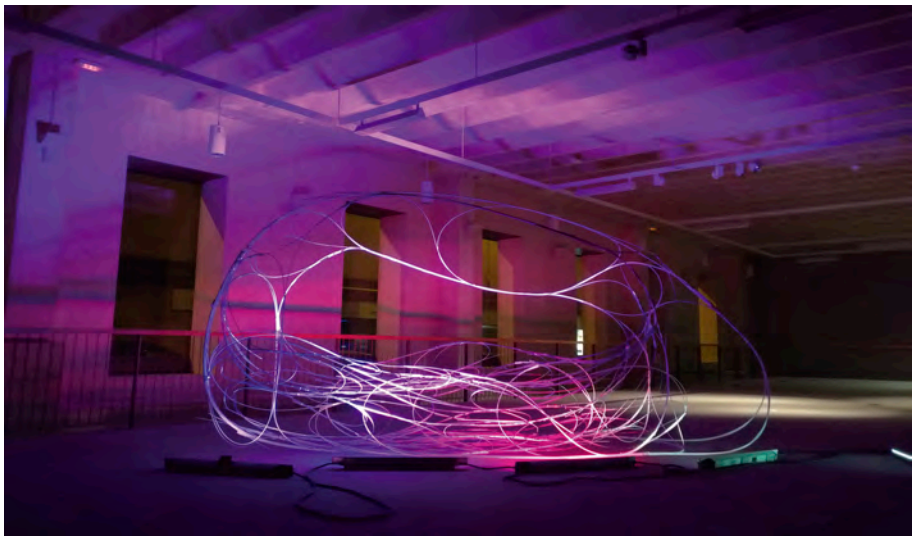


Figure 7. Final installation of the AAVS Madrid 2016 exhibited at the Colegio Oficial de Arquitectos Madrid (COAM) in July 2016, © Suzuki, 2016.

7. Conclusions

The main goal of this research was to extend the design space freedom in form-finding by implementing a rule-based object structure when programming the dynamic relaxation method. This is in part conceived through the abstraction and encapsulation of topological and geometrical data within different layers under the object-oriented paradigm. A circular reference of data between particle´s and element´s objects is implemented for continuously updating the vocabulary of the system. From here, grammatical rules described through object classes are then used to trigger geometric and topological modifications. Topology is stored in elements by referencing particle´s identifiers irrespective to its order with the intention of maintain a system of balanced forces. That is, connectivity is assured even if particles are sorted, unsorted, added, deleted or modified.

The topology-driven approach should not be understood as the mere increase of flexibility in numerical methods under an object-oriented approach, but rather it needs to be considered in the context of a novel computational methodology for form-finding that rises new design problematics for shape exploration and computation. This condition not only implies the development of more advance design workflows, but most important a deeper understand of rules and conditions that could permit reliable topological transformations on the physical system. In a broader view, topology-driven form-finding is the closest approximation to physical form-finding methods where material organization and behavior cannot be

separated. Yet, further questions regarding its uses and applicability in current design practice and architectural scenarios need to be answered.

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- Student team: Ana Taboada de Zuniga, Elliot Mayer, Facundo Taborda, Ipek Kuran, Iris Senel, Maria Rodriguez Jurado, Sukriye Robinson, Anna Shishkina, Kevin Moreno and Joey Ibrahim.

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PHYSAREALM

A Bio-inspired Stigmergic Algorithm Tool for Form-Finding

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Abstract. Physarum Polycephalum is a widespread eukaryotic microbe capable of producing effective networks between food particles to solve spatial planning problems. This paper investigates a previous algorithm for simulating Physarum Polycephalum. An open-source tool named Physarealm is developed for simulation in Rhino's graphical algorithm editor, Grasshopper. The tool adopts a previous stigmergic multi-agent algorithm for simulation and expands its boundary into three dimensions. In addition, this tool adds some custom rules, thus giving the designer more creative control over the produced results. Two research projects have applied this tool in the design process. The first project mainly takes advantage of the tool's path-planning ability, while the second one utilizes its aesthetic values, demonstrating the potential of the tool for further applications.

Keywords. Stigmergy; multi-agent systems; form finding; computation; biomimicry.

1. Background

Biomimicry seeks solutions to human challenges by applying strategies from nature. Researchers have shown that *Physarum Polycephalum*, a widespread eukaryotic microbe growing in nature, can solve several spatial planning problems. A group of Japanese researchers has shown that *P. polycephalum* can find the shortest route connecting two food sources when placed in a maze with two oatmeal flakes (Nakagaki et al. 2000). It is also effective at dealing with more sources. In a 2010 paper, *P. pocephalum* created a network similar to the existing Tokyo train system when oatmeal flakes were dispersed to represent towns on a map of the Tokyo area (Tero et al. 2010).

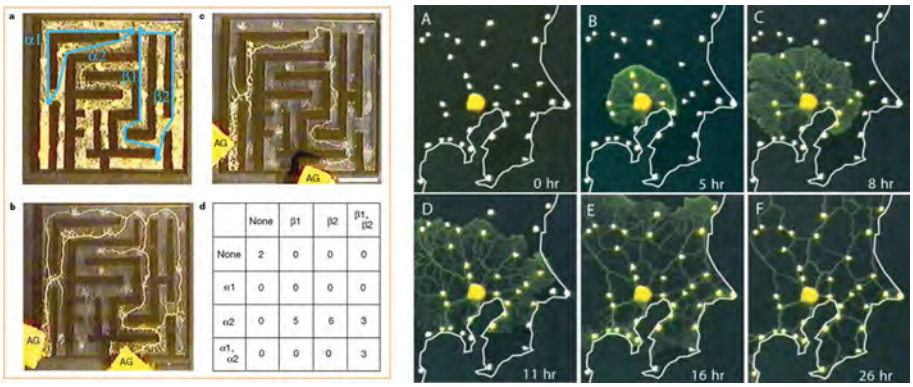


Figure 1. Studies on Physarum Polycephalum.

Inspiration from this natural phenomenon has raised questions regarding how we can mimic and emulate it to find solutions to path planning. Architects and urban designers often face spatial planning problems, such as finding effective paths between points of interest. Biomimicry of this organism's behavior will be helpful in solving these problems. In one paper, researchers applied the mechanism of *P. pocephalum* to the spatial planning of architectural design (Meyboom and Reeves 2013). In addition, *P. pocephalum*'s network can provide aesthetic inspiration. It is necessary to introduce a tool to designers that adopts this bio-inspired form-finding method.

2. Related Works

Several approaches have been proposed by scientists to simulate the behavior of *P. pocephalum*. The first approach applied the Hagen-Poiseuille law and Kirchhoff's circuit laws in a mathematic model (Tero et al. 2007). The second method employed the Oregonator, a model for oscillatory BZ reactions, to simulate its behavior (Adamatzky 2007). The third method utilizes a stigmergic multi-agent algorithm (Jones 2015). Among these methods, the third one produces results that are as good as the results of the others but is simpler and easier for designers to understand because it does not involve complex mathematical knowledge. These are the reasons for choosing the stigmergic algorithm in simulation.

Stigmergy is a mechanism of self-organization wherein agents coordinate through environments and collaborate to achieve a goal. The collective behavior of ants and termites are good examples of stigmergy that can be simulated using such an algorithm. In Jones's research, several simple individual behaviors were employed to create a model reproducing the biological behavior of *P. pocephalum* (Jones 2015). However, current methods of simulation have some drawbacks that must be addressed before they can be used in applications. First, it is difficult to integrate current methods into a designer's workflow due to the lack of interoperability. Implementation of the algorithm in the 3D modelling platform is required to simplify the exchange of data between 3D modelling software and the coding simulation environment and to reduce designers' difficulties when using it. Sec-

ond, the current stigmergic approach to simulating *P. pocephalum* mostly works in a 2D plane. There are few studies that extend the results into 3D space. This paper tackles the above-mentioned issues by implementing the algorithm in Rhino's graphic algorithm editor, Grasshopper.

3. Algorithm and Implementation

An open-source tool called *Physarealm* has been developed for simulating *Physarum Polycephalum* in Rhino's graphic algorithm editor Grasshopper. The tool adopts a previous stigmergic algorithm and expands its boundary into three dimensions so that agents can spread inside a Brep and generate spatial networks between points. In addition, this tool adds some new rules, giving designers more creative control over the produced results. This tool has already been released on Food4Rhino, and its code repository is on Github.

3.1. MULTI-AGENT MODEL

This expansion requires some modification of Jones' original model, including the agent's sensory behavior, motor behavior, growth and adaption behavior. In addition, we add some custom rules for creative control.

3.1.1. Overview

Agents can run in two scenarios, inside a Brep or on a Nurbs surface. The model for the Nurbs surface is similar to Jones's model in a 2D lattice and is thus omitted from discussion in this paper, except for replacing the planar Cartesian coordinates with Nurbs UV coordinates. However, the scenario for Brep is different. To expand the model into three dimensions, we utilize a 3D lattice base model for agents to move upon. Each agent represents a Physarum plasmodium particle. Another isomorphic lattice is employed to record each position at which the chemo-attractive trails diffuse over time in the environment. There are boundaries and obstacles. Lattice points inside the boundaries and outside the obstacles are capable of accommodating agents. Emitters in the model spawn agents near their locations and give them random orientations. Foods constantly emit chemo-attractive trails to attract agents through the high density of trails around them.

3.1.2. Sensory Behavior

Sensory behavior has major modifications compared to Jones' original model. The agent has multiple sensors to detect the level of chemo-attractive trail concentrations in front of it. All the sensors are on a sphere centered at the agent's location. We can describe sensor locations using four parameters in a spherical coordinate system. The coordinate system use the agent's direction as the z axis. *Sensing Offset (SO)* is the radial distance to each sensor. *Sensing Angle (SA)* is the maximum polar angle. *Detect Directions R(NR)* is the number of sensors at a particular latitude, and therefore the azimuthal angle between neighboring sensors at the same latitude $\theta = \frac{2}{NR}$. *Detect Directions Phy (NPhy)* is the number of sensors at the same longitude, and therefore the number i sensor at the same longitude has the

polar angle of $\phi = \dfrac{SA \cdot i}{NPhy}$. At each step, the agent iterates over all the sensors and obtains the one with highest concentration of chemo-attractive trails; the direction toward that sensor will influence its behavior together with *Rotate Angle (RA)*. The actual polar angle at which the agent moves is $\phi = \dfrac{RA \cdot i}{SA \cdot NPhy}$.

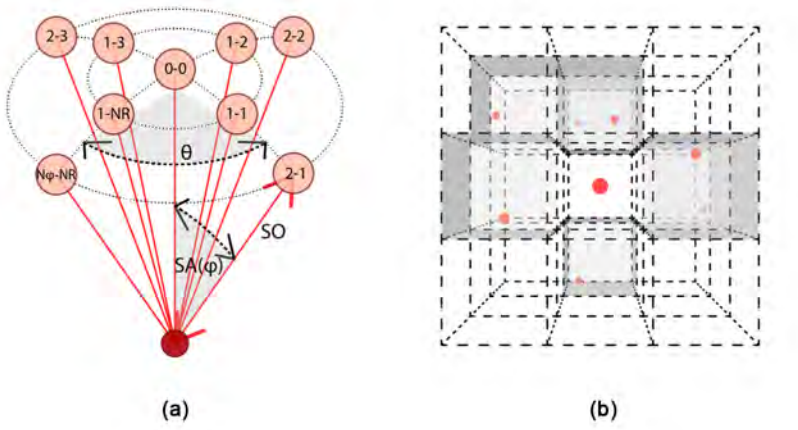


Figure 2. Senrory, growth and adaption behabior.

3.1.3. Growth and Adaption Behavior

As a simplification of the organism's growth and adaption, agents will divide into two when neighborhood space availability is high and die when the neighborhood is too crowded. The algorithm computes the number of agents within a local cube of lattices centered at the current agent location and compares it to certain parameters. The radius of the cube for division detection is *DvR* , and for death it is *DeR*; therefore, the length of the first cube is $2 \cdot DvR+1$ and the second is $2 \cdot DeR+1$. Let *n* be the number of neighbor agents. *DvMin*(>0) and *DvMax*($< (2 \cdot DvR + 1)^3$ for Brep environment) are the local division parameters, outside which growth cannot occur. *DeMin*(>0) and *DeMax* ($< (2 \cdot DeR + 1)^3$ for Brep environment) are local diminishing parameters, outside which the agent will be removed. For example, the algorithm will count 26 neighbor cells and check if any other agents have occupied them when $DeR = 1$. If the count of neighbor-occupied cells is between *DvMin* and *DvMax*, the agent will reproduce itself (figure 2b).

3.1.4. Chemo-attractive Trails Behavior

At each step, chemo-attractive trails in the 3D lattice are diffused by a simple mean filter kernel (typically 3*3*3). Next, the diffused trails are damped by a value *Dd* (typically 0.1). In addition to the diffusion, food and agents deploy trails into the environment, but they are not independent. A single parameter *TrRat* is used to

describe the amount of trail deployed by the agent to food after every scheduler step. The difference in both damping value and trail deploying rate affects the growth pattern.

3.1.5. Other Behavior

In addition to standard behaviors proposed by Jones, this model adds some behaviors for more creative control over the overall form. The first parameter is *Vertical Guide Factor (VGF)*, which affects the agent's movement. With a high *VGF*, agents tend to move more vertically, which is helpful for finding forms such as columns. The second is *Initial Velocity (IV)*. We can find this behavior in many multi-agent systems such as flocking, but we can hardly assume that Physarum can do the same. However, this behavior is important for initialing directional agents. The third is *Escape Possibility (EscP)*. A high *EscP* allows agents to escape the boundaries or to enter obstacles, which enables more stochastic boundaries.

3.2. IMPLEMENTATION

The algorithm is implemented as a plugin for Grasshopper. A typical program involves a group of inputs, a core Physarealm component and a group of outputs. Inputs include environments, foods, emitters and settings. Each type of input has a corresponding category of components on Grasshopper's component palettes (figure 3b). Output batteries are under the analysis category on the component palettes. Users can assign points or curves as foods and emitters, and Breps as containers and obstacles in the workspace. The program runs with a default set of parameters, but users can customize the simulation process by plugging in setting components into the core Physarealm component. A Boolean toggle and a timer control the start and loop of this program (figure 3a).

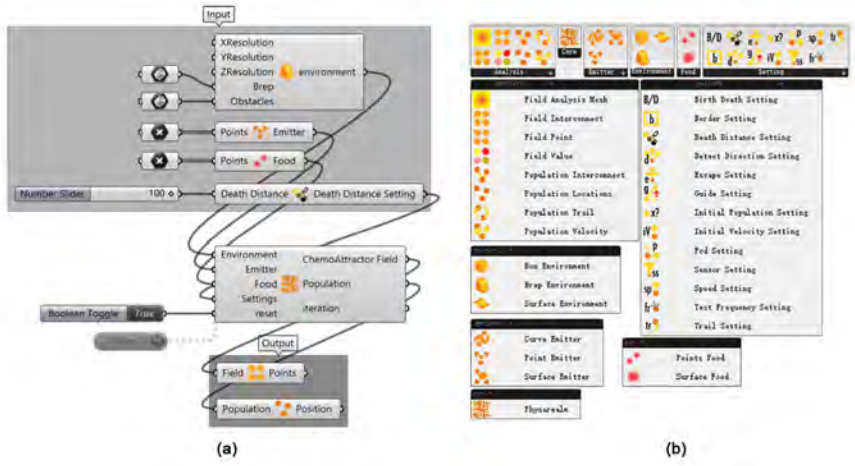


Figure 3. Usage and interface in Grasshopper.

Development of the plugin is based on Grasshopper's SDK. Implementation of components and data-types is inherited from Grasshopper's base classes, which separate the user interface from the back-end logic of the plugin. The code for logic is mainly implemented in the agent class(Amoeba) and population class(Physarum). Behaviors of the environment are implemented in each EnvironmentType class. The core algorithm is a modified version of a typical particle system algorithm, except that behaviors between agents and environments are different. A pseudocode is presented below.

```
InitilizaAgentsAndEnvironment
Loop
  updatePopulation
  updateEnvironment
  If( someCriteria )
    removeAgentTest
    divideAgentTest
  Endif
Endloop
```

Because this plug-in is open source with a code repository released on https:/github.com/maajor/Physarealm, this paper will not go into the details of the implementation.

3.3. EXPERIMENT

3.3.1. Approximation of Steiner Tree

A Steiner tree problem is a class of problems in graphs. It requires a tree of optimal interconnections for a set of given objects. This is an abstraction for designers seeking the shortest interconnecting route between POIs (Points of Interest). Most versions of the Steiner tree problems are NP-hard, while there are some algorithms to approximate them. The Physarum model in a 2D scenario gives an approximation as illustrated by Jones, and it also works well for the 3D scenario implemented in *Physarealm*.

The following experiments illustrate how *Physarealm* tries to solve the Steiner tree problems of four points. However, the four points are placed in 3D space rather than in a plan. The program loops for 2000 iterations before it reaches stability (figure 4a). The final shape between four points is an approximation of the Steiner tree in both left and front views (figure 4b).

3.3.2. Form Possibility

Apart from their interest in efficiency, as in the case of Steiner tree problems, designers also care about the potentials of the forms generated. We experimented with changing parameters hoping to exhaust the possibilities of forms. Several different forms can be generated (figure 5).

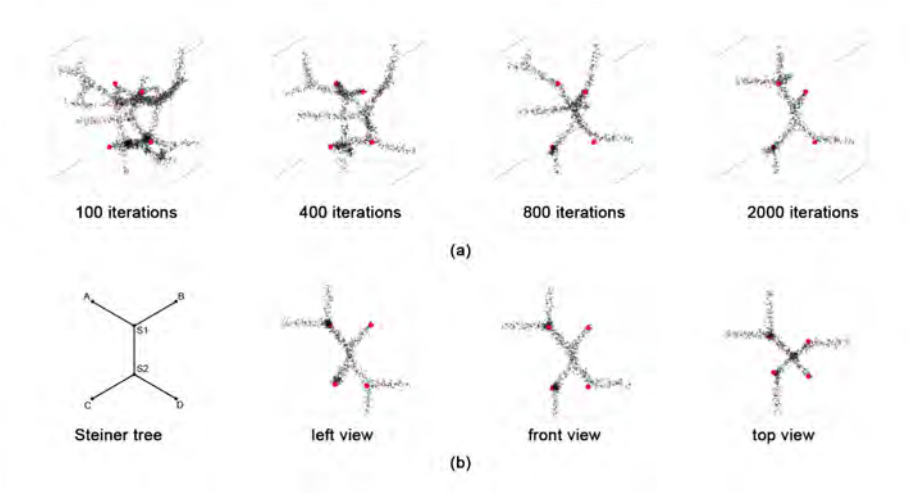


Figure 4. Approximation of Steiner tree.

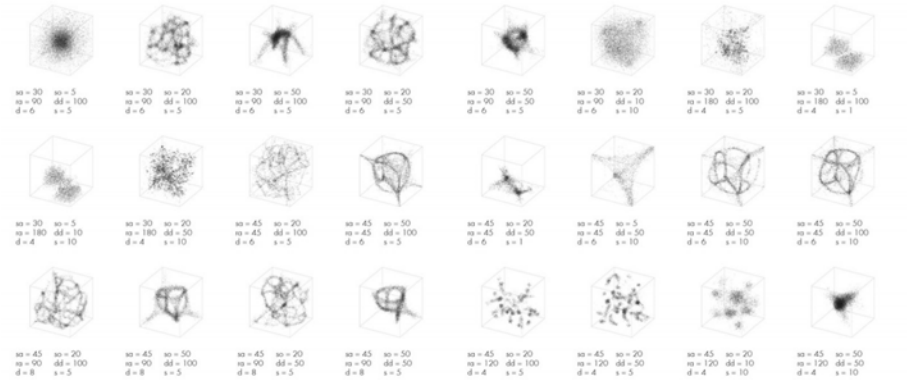


Figure 5. Form possibilities.

The plugin provides some components to visualize the simulated results. Functions include the density of the chemo-attractive trails (figure 6-1), interconnections of lattices based on chemo-attractive trail levels (figure 6-2), chemo-attractive trail levels at different heights (figure 6-3), interconnections of agents based on distance (figure 6-4), traces of agents (figure 6-5), locations of agents (figure 6-6) and velocity of agents (figure 6-7).

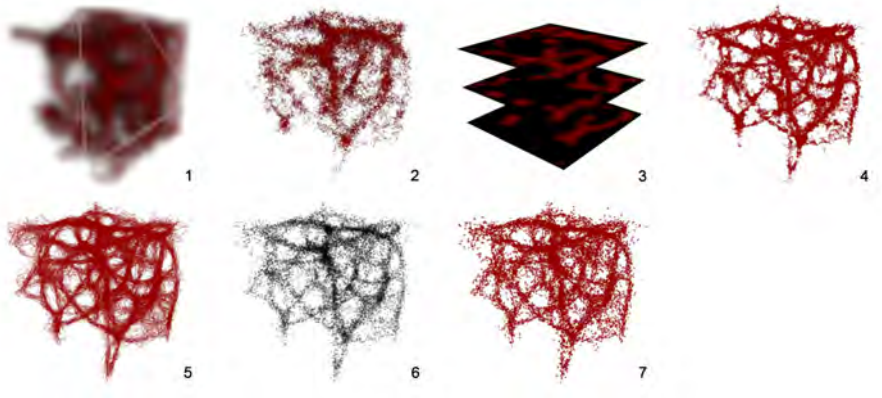


Figure 6. Visualization components.

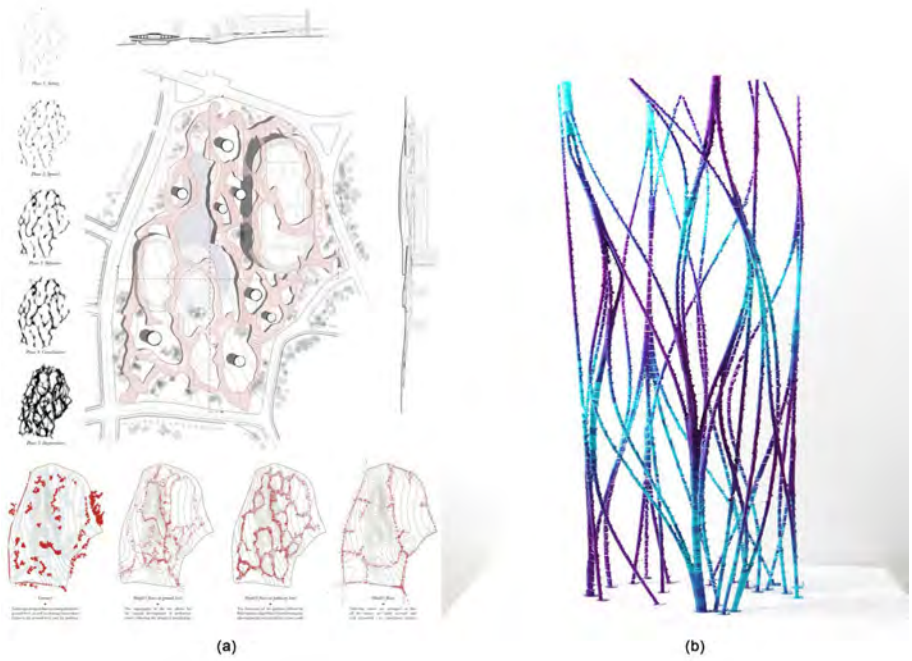


Figure 7. Applications in projects.

4. Applications

Two research projects have applied this tool in the design process, demonstrating its potential for further applications.

4.1. THE BLOB

The first project aims to build a new Olympic stadium that congregates several sports facilities (figure 7a). The strategy is to create a park pathway that allows people to reach all the venues easily. The formation of the pathway is generated using this tool. After setting the boundary and all venues as food in the workspace, the designer runs the simulation and obtains a network prototype for the pathway model. The network, just like the nutrient-ferrying tubes created by *P. polycephalum*, is strong, resilient and effective. The designers also considered expanding the project as a new type of fabric throughout the city. This will first occur in the perimeter and then spawn further, connecting and renovating empty areas with the pathway. Finally, the pathway acts as a net to knit the city fabric together.

4.2. FUSED SYNERGY

The second project fabricates a column-like prototype of approximately 30 cm x 30cm x 100 cm whose shape is created in this tool; within it, agents move vertically, leaving their traces behind as curves to be fabricated (figure 7b). Those curves are further simplified and optimized for fabrication. Through using stigmergic algorithms, we created an elegant weaving shape that is complex and unique. A multi-property FDM printer was designed and mounted on a robotic arm to 3D print this column prototype. The first project mainly takes advantage of the tool's path-planning ability, while the second one utilizes its aesthetic values.

5. Discussion

The algorithm discussed in this paper is similar to other stigmergic algorithms such as Ant Colony Optimization (Dorigo et al. 2006), but there are some differences. For example, in the conventional Ant Colony Algorithm, the agent's environment is often abstracted as a graph and path where a chemoattractive trail is deposited. However, in *Physarealm*, agents actually deposit and sense trails in 3D space.

This tool is able to simulate the behaviors of *Physarum Polycephalum* in 3D space, with some additional features allowing creative control over its form. Moreover, it is easy to use for form-finding, as shown in some research projects. However, there are still some limitations to this tool. First, the tool does not provide methods to evaluate planning performance. Quantitative studies of this algorithm's planning performance in 2D and 3D are lacking. Although the tool can approximate Steiner trees and create various forms, we need further experiments on which parameters influence its capability. As a result, validation of our application in projects is falling short. It is hard to measure whether the pathway finding is successful. Second, the tool functions well with Breps as its environment but may have bugs with Nurbs surfaces in Rhinoceros. These problems require further research.

Acknowledgement

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GENERATIVE DESIGN BASED ON SPONGE SPICULES' FORMS

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Abstract. A bio-based generative design approach is proposed with an application based upon sponge spicules. The approach aims to generate new valid architectural form finding methodology through the imitation of biological forms. The process includes five stages: Prototype Study, Imitation, Creation, Application and Fabrication. In the development of the approach, sponge spicules' forms, which are uniquely varied in the nature, are digitally imitated. Based on the imitation, a variety of formal outcomes are created. Some are suitable for architectural design and can be properly fabricated. Both the approach and the application on sponge spicules may contribute to the bio-based creative design exploration.

Keywords. Generative Design; Design Approach; Biomimicry; Sponge Spicules.

1. Introduction

The paper presents a bio-based generative design approach with an application based on sponge spicules. As the result of natural evolution, a variety of biological forms are highly developed with effective structural performance, material composition and function organization. Many of the forms have inspired sustainable design and the design of new material, product and structure in the past (Trotta 2011; Liu & Jiang 2011; Baerlecken et al. 2012; Peters 2011). However, the biological language and analogies in some researches have diminished humanity and human achievement in design (Kaplinsky 2006). Furthermore, most of these researches focus more on the imitation of natural forms rather than on their growth mechanisms; and the role of designers has been ignored.

In the presented approach, the biological and architectural knowledge are combined. The application of the approach is not only to get the well-imitated forms, but also to create more forms based on similar mechanisms and apply principles

extracted from mechanisms to the architectural problem solving. What's more, the designer plays a significant role in bio-based generative design by this approach.

In this paper, sponge spicules' forms are taken as an example to describe the new approach to bio-based generative design. Biological forms, similar to sponge spicules' forms, such as bone, phyllotaxis, cellular structures of wood and so on, have been well explored, showing a wonderful perspective of bio-inspired architectural form finding (Nsugbe & Williams 2001; Hensel 2006; Menges 2012). While sponge spicules' application in the field of architecture is still under-explored.

Sponge spicules have the potential to be developed into architectural forms. Sponge has been used as the prototype of minimal surface and parametric modeling (Vamvakidis 2007; Weston 2013); and its bone tissue has attracted architects by its highly differentiated structure (Weinstock 2006). Spicule has inspired material design because of its contribution to the structural integrity and strength of sponge (Aluma et al. 2011); and it has the potential to form mesh or honeycomb structure when assembled (Weinstock 2006).

Sponge spicules' forms are well-imitated and a variety of forms based on the similar mechanism are created with the following new approach. Both the approach and the process of generative design based on sponge spicules' forms are introduced as follows.

2. Approach

The approach to bio-based generative design is based on biomimicry to create new valid architectural forms. It has two main goals. One is to develop the attractive and efficient biological forms into architectural forms, which is based on the imitation of biological forms and the creation for new different forms. The other is to apply principles extracted from growth mechanisms of biological forms to the architectural problem solving. The foundation of the second goal is the similarity of biological adaptation and architectural optimization. In the nature, biological form never stops evolving to face the changes and challenges in the habitat and becomes more and more adaptable. In design, the designer modifies plans over and over again to find better solutions of existing problems and make the buildings fit the surroundings better. To this sense, the growth mechanism of biological forms may inspire the designers to find a new way for problem solving.

Five stages are included in the process: Prototype Study, Imitation, Creation, Application, and Fabrication (figure 1). Different from the previous biomimetic design, the designer plays an important role in the process.

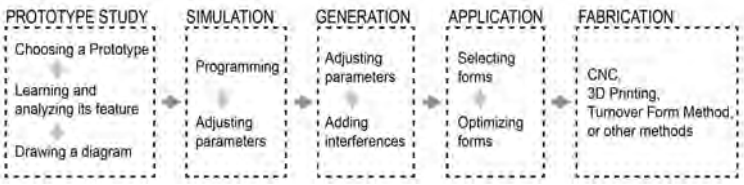


Figure 1. Five stages in the approach.

Firstly, Prototype Study is the basic stage and based on a primary investigation into the prototype. The prototype is butterfly, conch, coral, or other creatures and morpha in the nature. By analyzing its morphology and the growth mechanism, the prototype is described with a diagram.

Secondly, Imitation is based on the prototype diagram to make accurate imitation of the biological form. By programming with digital software, such as Processing, Python or Grasshopper, the prototype is accurately imitated when setting proper parameters.

Thirdly, Creation aims to generate new forms based on the prototype. On the basis of the program in previous stage, multiple novel forms different from the prototype are created by adjusting parameters or adding interferences. And the forms still follow the similar growth mechanism as the prototype and also resemble some of its features. Furthermore, although these forms are created based on biomimicry, the quality of the created forms depends on the creative and design ability, and aesthetic judgment of the designer.

The fourth stage is Application, and its main task is to select and optimize the forms for architectural use and further fabrication. Although multiple forms are created in previous stage, only few of them are selected. After selection, parameters and interferences in the program may still need to be changed to optimize the forms.

The final stage is Fabrication. Many different methods are used for the fabrication of different forms, such as CNC, 3D Printing, Turnover Form and so on. The main task is to choose a proper method and make a model.

Many of various biological forms in the nature can be developed for the architectural application by the approach introduced above. With the five stages, the approach can be easily adopted for form finding and generative design.

3. Process

In this part, the application of the approach based on sponge spicules' forms is introduced with five stages.

3.1. PROTOTYPE STUDY

Spicule can be found in most sponges (figure 2). It is of high diversity on account of the taxonomic richness of sponges (Butler 1961). And a morphologic classification has been made to identify and describe different sponge spicules based on "composition and general architecture of the individual spicules", "the form of the sponge" and the manner to "construct the skeletal structure" (Butler 1961). Their functions vary from providing mechanical rigidity to deterring predators (Aizenberg et al. 2004). And the functions imply that they may have the valid structure to serve as architectural forms. Also, their growth mechanism is interesting. Spicules are generally elongated with silica to the sclerocyte (Imsiecke et al. 1995). Once a spicule reaches a certain length, it protrudes from the sclerocyte cell body, and occasionally, sclerocytes generate a second spicule while the first one is still in progress (Imsiecke et al. 1995).

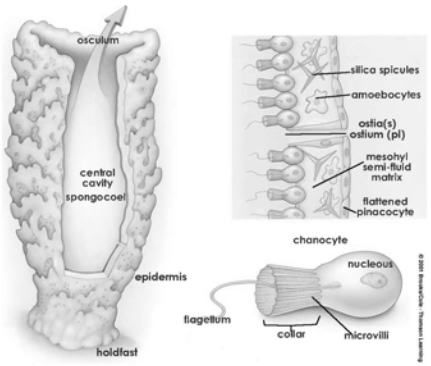


Figure 2. Spicules in a Sponge(extracted from Brooks/Coles-Thomson Learning 2001).

3.1.1. Feature Analysis

There are many different sponge spicules' forms in the nature (figure 3). And three kernel features are summarized as follows.

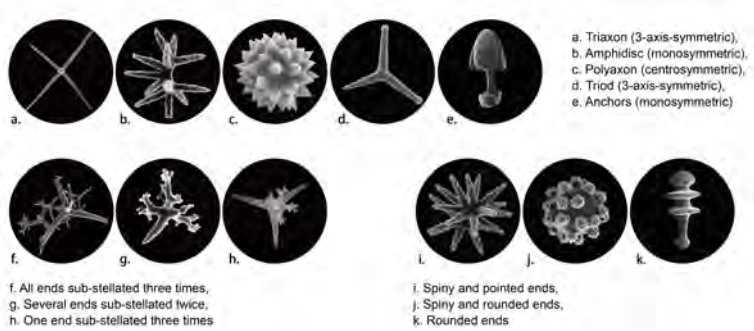


Figure 3. Various Spicules in the nature. a - from Van Soest (2009); b, i - from Cardenas & Rapp (2012); c-g, j - from Van Soest et al. (2012); h - from Muricy et al. (1998); k - from Lehnert et al. (2006).

The first one is the symmetrical axis. The number of axes in spicules varies from one to four, and even more, depending on species; and categorized by the number of axes, spicules are described as Monaxon, Triaxon, Tetraxon, Polyaxon, and so on (Andri et al. 2001). The second feature is stellated. For example, central symmetrical spicules are all stellated forms, while some spicules contain multiple sub-stellar with smaller branches expanding in one, several or all directions (Van Soest et al. 2012). Last of all, there are various mutations to spicules' ends. The ends are pointed, rounded, spiny, or very small sub-stellated branches (Van Soest et al. 2012).

Furthermore, some spicules with more than one axis, have axes bearing a similar ray, while others' axes lying in different planes (Andri et al. 2001). And some take irregular forms, while others form structures with an I, Y or X shape (Rigby & Boyd 2004; Bingli et al. 2003).

3.1.2. Diagram

Based on the analysis of sponge spicules' forms, most of them can be described by a diagram that includes the axis, the stellated and end's mutation (figure 4). Forms are generated according to the diagram.

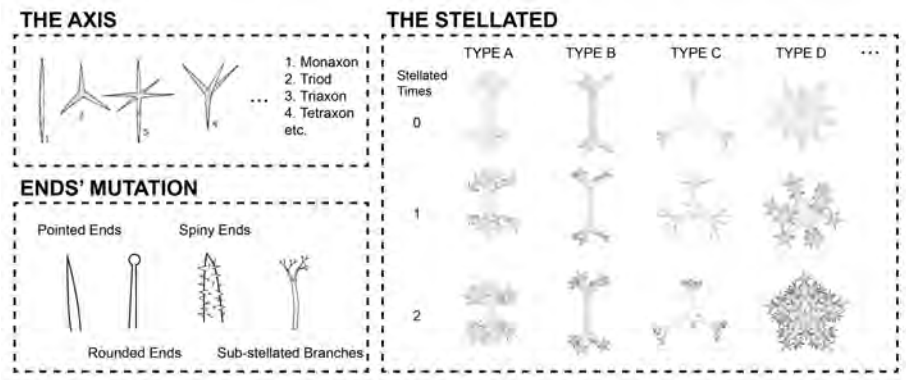


Figure 4. Diagram of sponge spicules' formation, from Thomson (1916).

3.2. IMITATION

Grounded on the diagram of sponge spicules' formation, forms are imitated by programming in Grasshopper. The process includes three stages according to the diagram. That is: Base Faces, Fractal and Ends' Mutation (figure 5).

At the first stage, Base Faces are created from base geometry. The base geometry is Sphere, Donut or Paraboloid (figure5-1A), and it will be tessellated into polygon faces or triangle faces (figure5-1B). Polygon faces are created by intersecting with Voronoi 3D; and triangle faces are derived from a physical method by distributing a set of vertices on the surface. After that, the faces of tessellated geometry are dispatched randomly by setting random numbers or evenly by the checkerboard tool (figure5-1C). Then, some faces are selected to serve as Base Faces which identify the form's symmetry axis.

Secondly, Fractal of branches makes the general form stellated. There are several kinds of branches branching off differently (figure5-2A). And the number of branches depends on that of Base Faces (figure5-2B). Then, several parameters are set to shape into intended stellated forms, such as Loop Number, Child Length and Child Radius (figure5-2C). Loop Number represents the time of branching off, and Child Length and Child Radius separately control the length of child branches and the radius ratio between child branches and parent branches. Also, other parameters build rules to make different stellated forms (figure5-2D). For example, each joint has two or three branches according to the distance to the parent branches (figure5-2D, Three Branches); the more origin's edges are, the more branches the first generation has (figure5-2D, More Branches); each joint branches off in the same physical way as the origin point (figure5-2D, Spherical Joints).

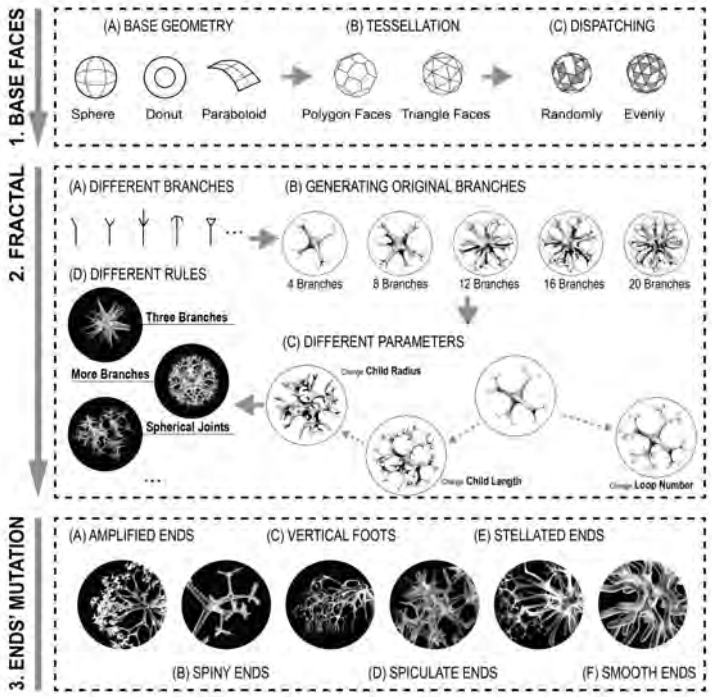


Figure 5. Process of imitation.

At the last stage, Mutation is performed to control the ends' shape of the form. There are six main kinds of Ends' Mutation: Amplified Ends, Spiny Ends, Vertical Foots, Spiculate Ends, Stellated Ends and Smooth Ends (figure5-3). Amplified Ends are amplified like horn mouth; Spiny Ends are similar to the spicules with lots of stiff sharp points; Vertical Foots are selected to touch the ground and provide structural support; Spiculate Ends are branches ending up as points; Stellated Ends are composed of many small stellated branches; Smooth Ends are created by simply smoothing out the branches' ends.

3.3. CREATION

Based on the imitation, different forms are generated by creating different Base Faces, changing the parameters in Fractal of branches, or choosing different types of Ends' Mutation. Besides, interference elements, such as curves and points, are also used for influencing the forms (figure 6-left). For example, when setting a single line, curve or circle as the interference, the form results as asymmetric; when using multiple lines, curves or circles as interferences, the form is symmetric but uneven; when using a set of points as interferences, the form performs as several flowers uniting together.

All in all, grounded on the imitation program, a large number of forms with different features are created by adjusting parameters and adding interferences (figure 6-right).



Figure 6. Interferences (left) and a variety of created forms (right).

3.4. APPLICATION

Among lots of created forms, some are potential to be applied into architecture. And the forms are optimized by proper selections in creating Base Faces and End's Mutation, well-adjusted parameters in Fractal, and adding interferences.

As the created forms are unique and attractive, it is possible for them to motivate the negative space in city. For example, a pavilion is designed as an exquisite object under the overpass in city to attract people and diminish the negative space (figure 7-left). While the overpass making the traffic more convenient, it also brought out negative spaces where crimes might happen. These negative spaces will be given a new life with the pavilion.

A ring-like form is selected and optimized as a pavilion. The ring-like pavilion is non-directional and attracts people from all directions. It is also a symbol of equality in city. Actually, the ring-like form is rare in the nature, so the combination of the ring-like form and the spicules' form will arise the curiosity. When lights around the pavilion are on, the lights and shadows create a wonderland-like atmosphere.

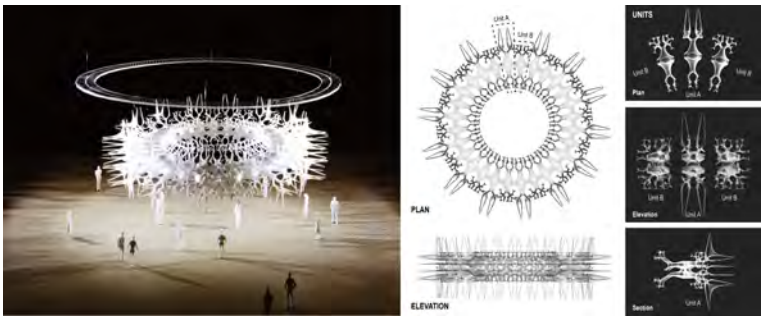


Figure 7. Architectural application as a pavilion and two units.

In order to create the form, firstly, Donut is used as base geometry and tessellated into triangle faces, creating a ring-like and centrosymmetric form. Secondly, Base Faces are generated by dispatching tessellated geometry and alternatively divided into two units: Unit A and Unit B (figure 7-right). Different rules of Fractal are applied to the two units. When growing outward, branches of Unit A protrude the longer spines (higher Child Length), while Unit B branching off more times

(higher Loop Number). At last, Spiculate Ends are applied to all branches, adding the concision and power of the pavilion.

3.5. FABRICATION

Taking the pavilion's fabrication as an example, two methods are used: 3D Printing and Turnover Form.

3D Printing is suitable for small and delicate model making. Its quality depends on the printer. The model printed with high precision has perfectly formed details (figure 8-A).

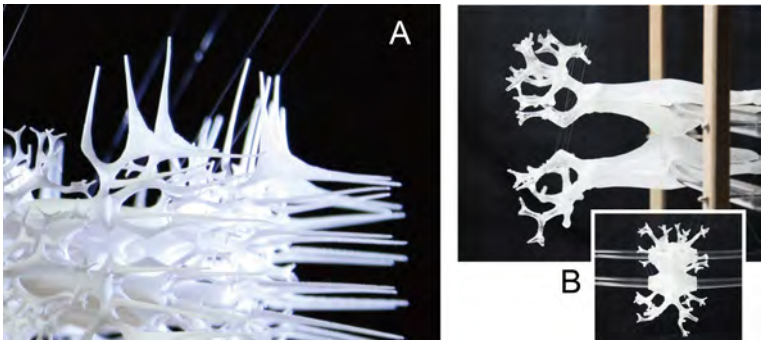


Figure 8. Model made by 3D printing (A) and Unit B made by turnover form (B).



Figure 9. Process of making model by turnover form.

The form can be fabricated by Turnover Form part by part, and this method is much cheaper than 3D Printing. Unit B of the pavilion is made in this way (figure 8-B). First, the unit is disassembled into many 3D parts (figure 9-1), and for the convenience of later process, the joints are designed to be connected without glue. Then, the 3D parts are sorted and each kind of them is 3D printed (figure 9-2). Afterward, in order to get duplicates of identical parts of the units, silica gel is used for mold to duplicate the 3D printed parts into many PU resin versions (figure 9-3). Finally, all parts are assembled together into a unit. And when enough units are made, they can form a whole model together. In this way, a lot of materials and time are saved.

4. Conclusion

The presented approach to bio-based generative design is valid, creative and efficient. Firstly, designers play a significant role in the process, contrary to the previous researches which diminish the effect of designers. The designers' creative ability and aesthetic judgment directly result in the created forms. As for application, designers need to select and optimize a potential result to fit the surroundings. Secondly, the form created by this approach imitates the prototype well and inherits its advantages on the basis of imitation program. Thirdly, not only the biological forms, but their growth mechanisms contribute to the architectural design. Because the imitation is based on the growth mechanisms, the program may simulate an adaptive process similar to the natural adaptation when adding interferences. This inspires the designers to apply the principles of the growth mechanism to architectural optimization. Finally, the approach with five stages is efficient for form generation and can be applied for a variety of biological forms. With the help of the advancing technology, chances are that many complex forms are created and optimized more efficiently. Also, the approach still needs to be developed to adapt to different natural forms better. In future, more and more natural forms would be used as prototype for bio-based generative design by this approach. And the approach will become more complete.

Generative design based on numerous and various biological forms, such as sponge spicules' forms, can create endless novel forms by taking the approach stated above. As for sponge spicules, forms created by this approach are varied, adaptable, buildable and harmonious. Because of the high diversity of sponge spicules, forms vary when taking different spicules as the prototype; as there are many parameters and interferences in the program, the form can be optimized by adjusting one or several parameters or changing interferences to serve different purposes; the form derived from spicules also inherits their logical structures, making it possible to be constructed; resembling spicules' features, the form is usually harmonious and complex.

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Interactive and Kinetic Architecture

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PROTOTYPING RESPONSIVE CARRIER-COMPONENT ENVELOPES

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Abstract. The capacity to respond dynamically to changes in external and internal environments open new possibilities in the interaction between buildings, humans and the environment. The development of dynamic envelopes requires the integration of various systems- geometric, structural, and electronic-responsive and their interaction. The paper reports the results from the "Dynamic Cloud Project" and presents a design and fabrication methodology to integrate kinetic behaviour with material constraints; the simulation of responses by connecting components with programmable input and behaviour. The paper presents a modular, component-driven systems construction based on a carrier-component surface geometry called responsive carrier-component envelope (RCCE) and describes the modelling, fabrication and assembly of such envelopes. The protocols developed in the project are reported in the paper and highlight the opportunities and consequences of how local components relate to the whole carrier envelope with multiple constraints and scale considerations. The results of the prototyping and experimentation with this project are reported in the paper. The paper also discusses future applications of the research and outlines new possibilities and design opportunities in prototyping responsive carrier-component envelopes.

Keywords. Dynamic envelope; carrier component mesh; sensor interaction; interactive architecture; digital fabrication.

1. Introduction

The research is inspired by formative ideas proposed in the sixties and seventies which speculated on the possibility of an indeterminate architecture responsive to uncertainty, incompleteness and emergent states. Urban utopian proposals by Archigram and Japanese Metabolists (Cook 1990; Maki 1964) speculated on a shifting assembly of parts that make up a whole while kinetic architecture of

William Zuk and Rogert H. Clark conceived of in the seventies envisioned moving components and entire structures adapting to the needs of its users (Zuk & Clark 1970). Nicholas Negroponte, a forerunner of the concept of responsive architecture, in 1970's built a body of work attempting to define and produce it by integrating computation into spaces and structures through recognition, intention, contextual variation and meaningful computed responses (Sterk 2003).

The two common themes that stem from these approaches is the ability of design to adapt to a variety of states akin to a real-time parametric model, changing the morphology and architectural understanding of part-to-whole relationships and enabling user's input and emergent situations to influence these states- achieving a more direct relationship between architecture, its occupants and their needs. In this sense, architectural design is invoked as an integrated spatial strategy with robotic protocols inseparable from the architectural design and its intent.

Today, these technologies are at the forefront of architectural research and can be broadly divided into two categories: digital fabrication/assembly and dynamic architecture. While the former has a clear agenda and a well-defined strategy as new means of production and communication of a digital design process to final outcome, the latter still remains somewhat elusive (Rosenberg 2009). While advances and accessibility of certain technologies in recent years allowed architects to experiment with ideas of interaction and kinetic actuation more directly, the larger question of synthesis- how all the disparate areas of knowledge and systems can be integrated into approaches that can be applied more directly to larger architectural structures remains unclear.

In this paper we look at the possibility and challenges of structural integration of dynamic envelopes. By looking at the example of the Dynamic Cloud project, we propose a design criteria which focuses on the interaction between part and a whole- how structure, interaction, materiality and geometry is impacted by assembling "smart" or complex discrete components into larger, potentially indeterminate wholes- what challenges emerge and how we may be able to systematically control these in the future.

2. Towards responsive carrier component envelopes

Computing technology is rapidly advancing and seeping into all areas of contemporary life and architecture. Responsive surfaces allow for interactive communication between people and their environment through the use of micro-controllers, sensors and actuators. Responsive envelopes have been classified into three broad categories in the literature, namely media facades (Mignonneau & Christa 2008) dynamic envelopes (Tomitsch et al. 2010) and interactive systems (Seitinger et al. 2009). This paper presents the concept of a responsive carrier-component envelope (hereafter RCCE), a physical prototype that dynamically integrates, environmental information in real time, and responds by changing its geometric state. The following features are used to define the design criteria for the development of the RCCE prototype:

1. The structural support grid and overall geometry should be defined by a carrier surface geometry. The carrier propose a self-supporting, integrated structural grid

geometry, avoiding peripheral structural or cladding elements;
2. The carrier surface should be decomposable into an aggregation of kinetic components. The kinetic elements are aggregated to minimise cost and complexity and provide a coherent integration between responsive and physical/structural components; and
3. Each discrete component should support open ended, reprogrammable sensor input-output with the environment. Components should be reprogrammable and re-configurable to allow a broader range of experiments with interactivity. The network should support accessibility and flexible placement of sensor infrastructure.

Our end goal is to make a self-supporting surface geometry using reciprocal kinetic components that operate on computation protocols and allow it to exhibit self-organisational properties. The Dynamic Cloud project brief was to design and prototype an RCCE for display and installation at the Shenzhen Maker Faire held in November 2016. The project was undertaken in collaboration between IdeaFactory (YunTech) and CodeLab (Curtin University) under the supervison of Carl Yu (OneWork.io), a startup company with expertise on Internet of Things (IoT). The aim of the project was to demonstrate an RCCE prototype using design-oriented fabrication approach. Design and research were conducted on multiple aspects of the process, remotely communicating between the teams in Shenzhen, Taiwan and Perth, Australia. The Curtin team focused on the design of the carrier surface and kinetic component prototyping while The YunTech team focused on the fabrication and making of the RCCE and put together prototypes, improved aspects of geometry and code and took part in the final assembly.

3. Theory Application

The core of RCCE is the assembly of larger structural surfaces from a collection of self-contained autonomous kinetic components that respond to sensor based interaction.

4. Carrier Geometry

Grid shells have been studied and applied to full scale built architecture by many practitioners and scholars. The carrier geometry of the RCCE was initially conceived of as a self-supporting parabolic grid shell that consists of multiple systems that allow (potentially) indeterminate bracing and structural support, kinetic actuation and communication and cladding layer which could expand the possibilities of what tasks the carrier component envelopes are asked to perform. The structural complexity of the carrier surface and lack of time meant that the parabolic structure was not pursued beyond the prototyping phase for the final installation. For tessellation of the geometry of the dynamic cloud project we used a simple surface triangulation that follows a hexagonal pattern (figure 1). The component nature of conical meshes on which global geometry is based creates opportunities for bottom-up approaches to component-based envelopes but presents structural challenges in relation to stresses and connections at vertices (Liu et al. 2006).



Figure 1. Prototype responsive ceiling design with kinetic component.

5. Kinetic Component Design

The self-organisation is constrained by surface geometry on which the component is aggregated. Parts have a degree of freedom in a complete system and work independently while responding to their neighbors effecting changes on the larger scales. This allows for a less deterministic part-to-whole relationships to emerge from interactions of local protocols and a multitude of external stimuli. In the current prototype, components in RCCE are comprised of scissor truss assembly based on Hoberman sphere (Hoberman 1990) guided by sliding arms and allowing a single degree of freedom in a symmetrically polar array. The components follow rules of local independence and global correspondence to form iterative responses and spatial configurations based on various local inputs (figure 2).

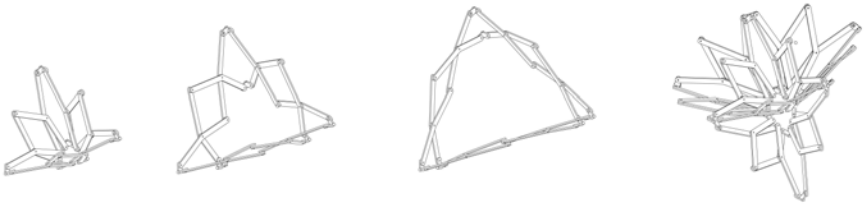


Figure 2. Early component configuration prototype models for kinetic components based on the scissor truss.

6. Sensor Interaction

Each component is an autonomous mechanism with an ultrasonic sensor (HC-SR04) driven by Arduino microcontroller. The sensor detects proximity of objects in front of it with a maximum range of 5 meters. Upon detection, it activates a geared motor connected to the kinetic truss through linear motion and begins contracting it. Once the sensor stops detecting or the collision switch is activated when

the truss is fully collapsed, the script pauses and proceeds to return the mechanism to its extended configuration.

7. Simulation and Prototyping

The RCCE is prototyped with top-down and bottom-up approaches using modelling and scripting techniques to get information about geometry and kinetic properties of the prototype. In the bottom-up approach, the scissor truss assembly derived from four sides of a dodecahedron is used to generate geometry in Grasshopper and simulate its movement using a spring system in Kangaroo (figure 3). The complexity of the assembly and its kinetic actuation, variation of parameters and scale are tested.

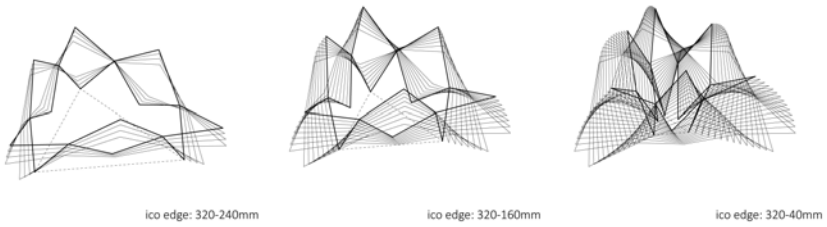


Figure 3. Simulation of component motion.

The top-down approach involved creation of a grid shell surface structure for carrier components. One of the challenges with introduction of a curved structural grid is variation in the geometry of parts. This presents significant challenges in terms of assembly of complex interactive components. Originally, the structural grid fabrication was based on the approach presented by Andres Sevtsuk and Raul Kavlo in the SUTD pavilion (Sevtsuk & Kavlo 2014). However, this approach was replaced by a simpler carrier surface. The next step was to standardize kinetic component parts, namely the guiding rods to fit the curving surface. A standardization script was developed (figure 4) that fitted equilateral triangles using geometric transformation per face (Yaglom 1962). If the face is too small, the solution is culled. However, this causes several problems- orientation of components is misaligned with the original diagrid geometry, also the connection of the rod to the outside support structure generated variable insertion angles that proved intractable in the fabrication process. For the Shenzhen fair we settled on planar surface tessellation with equilaterals and separated the structure from the kinetic component grid. This design compromise simplified the kinetic component and enabled the delivery of local interactions without structural ramifications.

8. Material Assembly

The basic unit is built on a triangle containing tetrahedral scissor truss geometry (figure 4). Structurally, the components are made of three main parts: the struc-

tural frame that houses all the parts and connects it to its neighbors (1), guiding rail assembly which contains all sensing, actuating and logic components (2) and kinetic scissor truss assembly (3). 34:1 motor connects to three linear belts that are guiding the base points of the truss. There is a binary switch that communicates to the script terminal position of the truss under maximum contraction.

A flexible multi-axis 3d-printed connectors allow us to connect the kinetic scissor truss to a planar rail frame which can be animated by linear motion. Early prototypes contained springs which kept component in tension while the final prototype used timing belts and motors to control position more precisely and eliminated kinetic energy which made motion more unstable given relatively large number of parts per truss. The design uses a number of standard industrial components like steel shafts and connector brackets to reduce construction time and cost (figure 4). A few 3d printed components were used to connect assembly at key intersections with unique angles. In this case, 3d printing is used as part of the combinatorial approach to construction where many different materials and parts come together as oppose to creating complex, continuous forms.

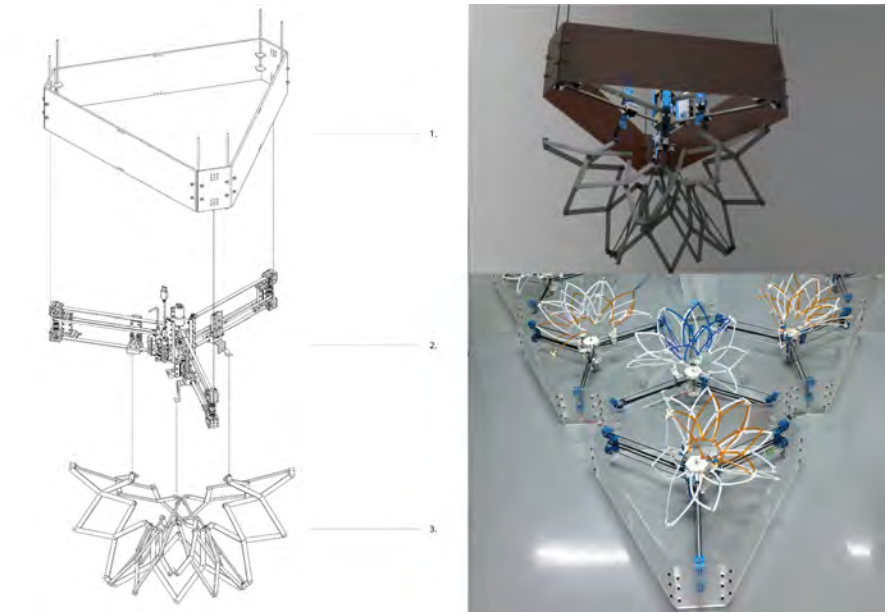


Figure 4. Final component assembly (left) and Design variations of 3d printed joints and connectors (right).

9. Control System

Control system uses standard Arduino IDE written in C for individual components with the controller script being uploaded to local microcontroller boards mounted on the structural frame. The microcontroller is connected to the motor, ultrasonic sensor, an LED strip and a switch to determine position of the kinetic truss. This

allows components to 'sense' presence and proximity and respond by retraction or contraction. The precise timing allows for real-time control and synchronization of motor positions in relation to external stimuli.

10. Exhibition Prototype

Over the period of three weeks, the teams communicated and exchanged 3d models, scripts and other documentation relating to prototype construction. The Curtin team assembled design documentation while Yen Tech team prototyped various design iterations using digital fabrication equipment at their facilities before proceeding to install the prototype on site in the Shenzhen MakerFaire. The final 1:1 scale prototype was realized with three days of on-site construction made out of 16 fully-assembled and functional components which were fixed to a stable temporary structure with steel cable rods (figure 5). These arrangements provided the right constraints for the model surface to be suspended over temporary public space allowing for minimal lateral movement and interference between components. Components performed interaction with no identifiable failures over the course of three days.



Figure 5. RCCE final installation and interaction at Shenzhen Maker Faire, November 2016.

11. Conclusion

The results of the prototype experiments for the development of responsive carrier component envelopes are:

1. the development of the carrier surface and its subsequent articulation with components requires geometric resolution at two scales. The tessellation of the carrier surface must be rationalized to account for both part-whole relationships as well as control of component variation and scaling.
2. the digital to physical translation from rationalized geometry to material requires further inputs in the selection of materials, their tectonic properties as well as a consideration of their assembly; and
3. the incorporation of responsive elements in the form of electronic components and sensors requires careful consideration of the interaction logic, input-output behaviours as well as sizing and resolution of components. An important element in interaction design is the trade-off in resolution- density of components corresponding to the component positioning. Denser iterations produce greater resolution but create more complexity in terms of set up and fabrication as well

as driving up costs.

The RCCE is an experiment in architectural design that gives us insight into construction of complex architectural assemblies incorporating digital fabrication, dynamic forms, system design and planning. RCCE is work in progress and due to its complexity and wide range of interdisciplinary knowledge required, will require expended collaboration in the future. The main problems encountered are structural- control required to script and test a largely bottom-up system in terms of its structural dynamics and force distribution is considerable. Although the behavior is emergent- the form still remains static. This problem will be addressed in further design iterations to control the local parameters influencing the surface tessellation and have more control over aggregation of local geometry into a larger whole. This could be expanded upon by looking at the way components connect, degrees of freedom allowed per component and the way cladding layer can be arranged more continuously rather than a collection of disparate kinetic scissor truss assemblies. The future implementation will include communication protocol between components to allow for coordinated transformation of the structure.

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HUMAN-COMPUTER INTERACTION IN THE FORM-MAKING PROCESS

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Abstract. Many elements of architectural design are becoming automated, and the boundaries between design, construction, and use are increasingly blurred. These developments have produced concerns that our design processes might outrun "human factors" in our search for novelty and automation. At the same time, however, this new technology can also improve our opportunities to develop human-centric environments. This paper describes the creation of an interactive form-making exhibit called ROBOBBLE, and the use of this installation to engage users in design while collecting data about their architectural preferences. The ultimate goal of the ongoing project is to learn more about human form creation and architectural evaluations, and to integrate those findings into computational design algorithms and pre-design toolkits. A pilot study was conducted to test ROBOBBLE as a data-collection platform and to evaluate interactive form-making engagement among a small group of students. The platform was shown to be successful in engaging all of the participants in this pilot study and expanding their creative design capacities over time. Future work using ROBOBBLE for larger population studies has the potential to produce detailed data about a wide variety of design preferences, and to incorporate this data directly into computational design process.

Keywords. Human-Computer Interaction; Form-Making; Human Data; Design Process.

1. Introduction

The exponential growth of information-processing technology has given rise to an increasing reliance on computational approaches in architecture. These approaches often remove important aspects of the design process from direct human

control. In some cases the entire cycle of form-making, evaluation, and the selection of form alternatives is being carried out computationally. The rapid development of such approaches in architecture raises the concern that the full richness of human experience and evaluation may no longer be present in certain aspects of design, and that a gap may arise between the architect's direct awareness of human needs and the ultimate, computationally-assisted design outcomes.

This study contributes to cutting-edge research efforts in computer-aided design by analyzing the abstract form-making process in the human mind and developing better methods to replicate this process in computational problem-solving. By gaining a better understanding of the current boundaries between designers' visions and computational outcomes, the researchers aim to develop an improved model for incorporating rich human data into the computational design process.

2. User-centered Design Cognition

Architecture is not only a process of creating physical shelter and functionality; it also has a responsibility for promoting psychological and social wellbeing (Leatherbarrow 2009, p. 8). Today we have a wealth of knowledge about human psychological responses to the built environment. Neurobiological approaches to design problems offer a valuable means of understanding both the human response to design and the design process itself. (Sternberg & Wilson 2006). A number of important studies have been conducted from a neurological standpoint to analyze occupant reactions to architectural form (Martínez-Soto et al. 2013; Nanda et al. 2013) as well as the behavior and mental processes of architects as they approach design problems (Cross 2001; Rowe 1991; Schön 1983).

The act of designing a building is intimately connected to the eventual user experience of the design outcome. This insight is not new in the design field; Benedikt (1979) described it as the need "to design environments not by the initial specification of real surfaces but by specification of the desired (potential) experience in space." Béguin (2003) characterized design as a mutual learning process between users and designers. Bannon (1991) emphasized the need to focus on the users of architecture as people in social situations, with specific skills, needs, and shared practices, and to integrate this awareness into technology and design. Schneider and colleagues (2013) described an "inside-out" approach to design that develops the geometry of a building from the user's perspective and based on user needs.

For all of the reasons described above, pre-occupancy evaluation and research into user perspectives is a vital and growing field in architecture, design, and environmental psychology. Design researchers are conducting exciting studies that expand the frontiers of knowledge in this area. Kumar and colleagues (2011) developed an Augmented Reality interface that allowed users to review potential design alterations in healthcare facilities and to provide feedback on these variations. Kalantari (2016) similarly used Augmented Reality to evaluate the relationship between urban architectural forms and human stress responses, incorporating physiological measurements of stress as well as self-reported reactions. Kuliga and colleagues (2015) analyzed user experiences in fully virtual environments to

evaluate redesigns to an existing building layout.

Researchers are also seeking new methods to incorporate user input directly into the design process. Schneider and colleagues (2013) developed a multi-faceted approach in which feedback from users as well as from experts in cognitive and environmental psychology is integrated into design studio processes. Jelić and colleagues (2016) drew from phenomenological philosophies to develop what they call an "enactive" approach to design, which is grounded on the understanding of the designer as an embodied organism existing in connection to larger social and natural processes.

The concept of user experience has become foundational in the literature of human-computer interactions and technological product design. In this context, user experience is defined as the highly individual preferences, emotions, motivations, psychological responses, and behaviors that mediate interactions with built objects (Hassenzahl 2010). The investigation into user experience as it relates to technological products has provided a template for many architectural post-occupancy studies, in which user reactions are gathered to evaluate the success of an implemented design. This connection is explicitly noted by a number of post-occupancy researchers (Franz & Wiener 2007; Hölscher et al. 2006; Kuliga et al. 2013). Today's design technology provides exciting opportunities to integrate these user-experience analyses directly into design methods, so that feedback can be obtained before an architectural edifice is constructed, and even to make end-user input an integral part of the computational design process.

To incorporate user feedback into computational design, it is necessary to analyze the conceptual processes through which human designers and users evaluate a potential form. As noted above, there is exciting work being done in this area using Virtual Reality and Augmented Reality platforms. Today's technology allows us to go even further, however, in observing how users engage with computer-mediated, flexible design products. Studying user interactions with advanced adaptable designs is a valuable source of information and inspiration for architects who are seeking to develop automated design processes (Krukar et al. 2016).

3. Method

This research is an experiment in data-collection and data-analysis to help develop more responsive computational tools for architects. The purpose is to put the human user at the core of computational form-making. By analyzing user interactions with flexible design products, we lay the groundwork for allowing algorithmic design processes to absorb more inputs in terms of human needs and desires, and then create more responsive, effective outputs on the basis of that data. To accomplish these goals we have developed a flexible physical installation that allows users to experiment with design adaptation through real-time interactions.

3.1. DESIGN

The installation, named "ROBOBBLE," incorporates and expands upon earlier work in which designers and researchers attempted to fabricate smart two-

dimensional surfaces that would alter their form to satisfy specific movement-based behavior scenarios (Probst et al. 2011; Raffle et al. 2003). In this case, however, the installation is not limited to a two-dimensional surface or specific design contexts; it is a three-dimensional object that can be continually transformed through user interactions.

ROBOBBLE (shorthand for ”Robotic Bobble”) was originally conceptualized as an interactive art exhibit; it has now also come to be seen as a valuable means of collecting rigorous and extensive data about user interactions with architectural forms. The installation employs a flexible mesh and tessellated fabrication method. Through the use of a smart-phone app allowing simple push, pull, and soft-transformation commands, users who interact with ROBOBBLE are able to create customized forms in physical space (figures 1, 2 and 3). The sculpture constantly changes based on different audience members' taste and input, blurring the boundaries between designer and users. The cell phone application also allows the researchers to collect detailed data about users' inputs and their responses/adjustments to different design configurations. The aesthetic and playful side of ROBOBBLE belies its serious purpose in demonstrating new ways of bridging the digital and physical worlds and integrating user input into computational design.



Figure 1. Conceptual rendering of the ROBOBBLE interactive form-making installation.

3.2. FABRICATION

The basic material-technical system of ROBOBBLE consists of spandex fabrics covering a dandelion-like core of linear actuators. The core is a CNC milled plywood twenty four faces, where each face contains an actuator that moves perpendicularly to the face. We tested different types of linear actuator for the project, while considering the requirements of cost, weight, length, and speed, before settling on the existing arrangement. The actuators are powered using transistors in an H-Bridge configuration.

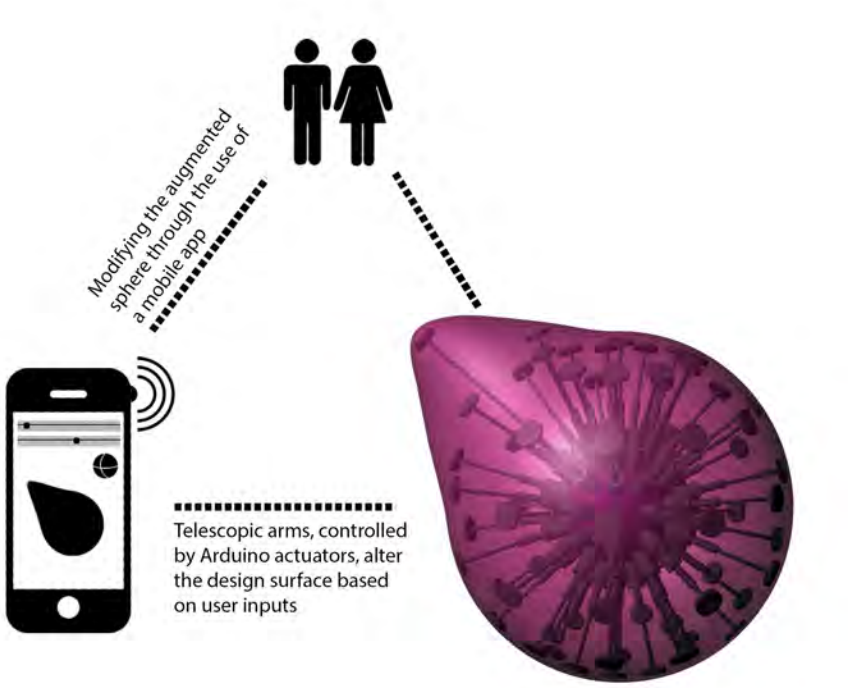


Figure 2. User interaction in the form-making process are carried out through the ROBOBBLE app, designed for smart phones.



Figure 3. Variable forms of ROBOBBLE can be created through the use of 24 linear actuators.

The Arduino Mega kits and servos that control the actuators are located inside the plywood core and receive instructions from a design-oriented cell phone application using Bluetooth technology. The end-arms of the actuators (made out of Styrofoam) create soft connections with the surrounding spandex fabric shell. The shell itself has the capacity to expand up to 2.5 times its resting size, which allows the overall geometry of the sculpture to take on a variety of forms and scales (figure 4 and 5).

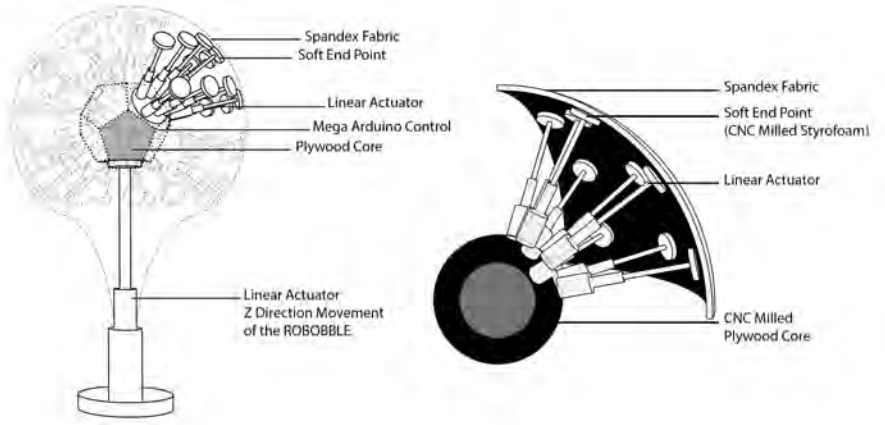


Figure 4. Detail of the ROBOBBLE core, the connection of the linear actuators to the core, and the connection of structure to ground.

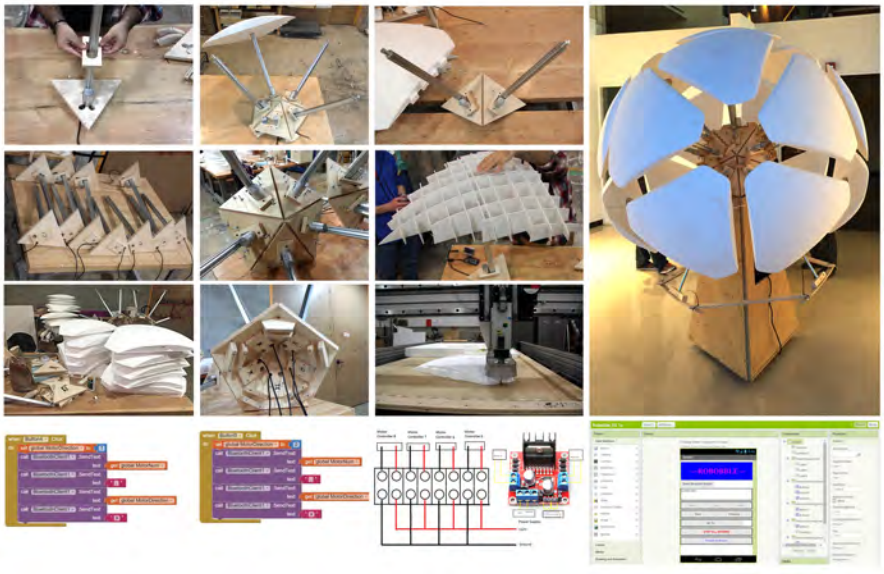


Figure 5. ROBOBBLE fabrication process.

3.3. INTERACTION AND EVALUATION

The users who interact with ROBOBBLE must first provide informed consent, download the project app to their smart phones, and answer a few demographic questions. They are then introduced to the simple and user-friendly tools that will allow them to adjust the installation's form. As they engage with the design, their inputs and responses are anonymously collected for analysis. The goal of the data collection and analysis is to evaluate the users' perceptions of form and the manner in which they go about producing a form that fits their needs and goals.

This paper reports the results of a pilot study that was conducted to test the use of ROBOBBLE in collecting data about design inputs. The purpose of this pilot study was to collect exploratory/qualitative data that can later be investigated in a more rigorous fashion. Ten undergraduate students participated in this pilot study, including five who were majoring in design fields and five who were in non-design majors. Each student interacted with ROBOBBLE separately, using the cell-phone app to generate a unique form. The installation was set to a simple sphere (null position) before each participant entered the exhibition room, and each participant was given a total of 20 minutes to create their design. The other participants were then asked to analyze, rank, and discuss each design. We repeated this process three times, allowing the students to learn from the previous round and experiment with new ideas (thus, 30 designs total). At the end of the study we held a focus group discussion with the participants, encouraging each of them explain their experiences and talk about the forms that they generated.



Figure 6. An early prototype of ROBOBBLE at Washington State University Fine Art Gallery .

4. Results and Discussion

During the first round of student designs (10 forms), we observed significant differences in outcome between the students with design backgrounds and those who lacked such background. The forms generated by design students were ranked higher by all participants and tended to be explained with words such as "creative," "meaningful," and "art." In the first round of peer evaluations, the five forms created by design students were ranked as the top five, while those created by other students were ranked as the bottom five. However, this division did not hold in the second and third rounds of form generation, during which the non-design students gained ground and in some cases created forms that surpassed the peer rankings

given to the products of the design students. This result seems to affirm a great potential for interactive design as a learning mechanism.

During the focus group, all ten of the students agreed that they learned from their peers' designs during the course of the study, and most of them regarded the process as being entertaining and engaging. Some of the students even asked if they could continue for additional rounds in order to try out new ideas. The majority (8 out of 10) stated that during the second and third round of form generation they had sought to create more semantic designs that would convey a particular meaning. The students agreed that these later rounds produced more creative and superior results. More concrete data gathered during the study supports this evaluation, indicating more complex and careful geometries. The number of actuators engaged during the first-round designs averaged 9.45 (out of 24). In the second round this number rose to 11.76, and in the third round it rose again to 14.43.

From the limited basis of this initial pilot study, it seems that experimentation with interactive physical form-making using ROBOBBLE led to meaningful learning experiences and engaging opportunities for creativity. The ongoing work in this project will give us ample opportunities to gather data on human preferences during the form-generation process. Ultimately our goal is to assess the types of learning and experimentation that lead toward better-received design outcomes, and to incorporate this knowledge into algorithmic processes and pre-occupancy design evaluation toolsets.

5. Conclusion

The design, fabrication, and implementation of ROBOBBLE involved a forward-looking collaboration of researchers from the architecture, psychology, and robotic-engineering fields, incorporating diverse technologies into a seamless product. Bringing these different sets of technologies together in design and fabrication reflects the future of the form-generation process, which will increasingly integrate active human behavior with form design. The use of real-time, linked digital and physical form-making expands the boundaries of the architectural medium, and has the potential to be a transformative tool in the hands of designers and artists. The results from this ongoing study allow us to better understand preferences and processes in attaining design solutions, and to more fully integrate those human preferences into computational design algorithms. By expanding the boundaries of human-computer interaction in design, we can gradually merge formal studies in digital space with hands-on conceptualization in the physical world, thereby heightening the qualities and possibilities of both approaches. A wide range of implementations of this research are possible, from programs that simply assist designers in collecting data and exploring the possibilities of form, to fully automating greater portions of the design process with more effective results.

6. Limitations and Future Work

The results reported in this paper are for a pilot study, and cannot be generalized to larger populations. Our project is still in its initial phases and we are excited about the multitude of possibilities in design research that the use of the ROBOBBLE

system will enable. In the next phase of the research, users will engage in a hybrid digital/physical experience that includes a parametric modeling platform, which is a significant expansion of our initial phone app and will allow for more detailed design explorations through a specifically designed input device. This development will increase our capacity to collect precise data about design processes and form-making preferences.

Future work may also see new developments in the physical ROBOBBLE system. One notable point of feedback that we gained from our pilot study participants is that they often felt a desire to "look inside" the ROBOBBLE structure, so that they could see the result of their designs in terms of interior spaces. This is not possible in the installation's current configuration, but it may be addressed in the future by expanding the size of ROBOBBLE and adding viewports. The current form of the installation is also somewhat limited by the flexibility range of the exterior mesh and the need to fix the structure to a stand (rather than hanging it from the ceiling). These limitations may be addressed in the future project development, allowing even more possibilities for users to experiment with form.

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ASYMMETRICAL DOUBLE-NOTCH CONNECTION SYSTEM IN PLANAR RECIPROCAL FRAME STRUCTURES

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Abstract. Reciprocal Frame Structures (RF) have broad application potentials. Flexible to using small available materials, they span large areas, including varied curvature and doubly-curved forms. Although not many buildings using RF have been constructed to date, records indicate RF efficiencies where timber was widely used in structures predating modern construction. For reasons of adaptability and economy, advances in computation and fabrication precipitated increase in research into RF structures as a contemporary architectural typology. One can observe that linear timber such as rods and bars feature in extensive RF research. However, interest in planar RF has only recently emerged in research. Hence one can argue that planar RF provides depth to explore new design possibilities. This paper contributes to the growing knowledge of planar RF by presenting a design project that demonstrates an approach in notching systems to explore design and structural performance. The design project, the developed design workflow, fabrication, assembly and evaluation are discussed in this paper.

Keywords. Reciprocal Frame Structures; Space Frames; Computational Design; Digital Fabrication; Deployable Architecture.

1. Introduction

Reciprocal Frame Structures (RF) continue to be popular as a research topic due to their diverse tectonic capabilities, works of Baverel, Larsen, and Pugnale, to name a few (Baverel 2000; Larsen 2008; Pugnale et al. 2011). RF comprise a family of structural systems characterised by the interdependent relations of their constituent parts (Danz 2014), where each beam supports and in turn is supported by all of the others (Larsen 2008). The concept of the reciprocal frame can be traced to prehistoric building types (Danz 2014). However, in recent years, developments in computation and fabrication motivate designers, architects and engineers to use RF when exploring form and elaborate structures. As well, studies by Nelson & Kotulka (2007) suggest that RF systems can potentially achieve infinite load paths

that can lead to structural efficiency. As mobile and rapidly assembled structures play a major role in contemporary society where speed of response is of primary importance (De Temmerman & Brebbia 2014), hence the paper argues, planar RF structures can offer solutions and be beneficial in such situations. As well, as our global resources are subjected to greater pressure, mobility and availability renew the role of human agents predating the introduction of modern building. This is evidenced by small-scale fablabs to a new shift in DIY full scale RF assemblage of rods and bars featured in most research projects. In this paper we also show that like linear RF, planar RF's prolific network results in elaborate jointing producing design opportunities.

1.1. OBSERVATIONS

RF's significance in design and construction predating modern techniques is explored in new ways with advances in computation and fabrication tools. As computation and digital fabrication require specialisation, the development, design and production of these structures usually remain exclusive. Although, as these structures are mainly assembled through physical labour, the role of human agents has never been more evident in such pursuit. How can this gap be lessened to create a more inclusive culture in the practice of RF? Potentially traditional means that enable the production of RF can be adapted and integrated in the process. Especially with more complicated RF designs, jointing for their prolific network usually mean they are too complex and expensive to produce, or, are not always structurally effective as a building for end use.

1.2. RESEARCH QUESTION

In considering these observations, the paper aims to address the research question: Can traditional means of building be adapted and integrated to avoid custom and mechanical devices that may not be readily and easily available, when exploring and investigating planar RF as a potential contemporary architectural typology? Based on the research question, the objective of this paper is to present the method of asymmetrical double-notching at the intersection events as contribution to the growing knowledge base for planar reciprocal frame systems.

1.3. METHODOLOGY

Drawing on findings in research by Puyol (2015) and Baverel & Pugnale (2013), the research used a design research method to develop a 1:1 scale prototype of a multi-unit quadrilateral reciprocal frame system with three dimensional capabilities (Tong & Zhou 2016) designed and developed for the Vivid Sydney Festival in Australia.

2. Reciprocal Frame Structures

Mandala roofs, weaving structures, tensegrity, nexorades, 3D and planar grillages are commonly associated with RF structures and share many design principles. Typically, the use of linear materials such as rods, bars and beams features in many of the well-known RF projects to date (figure 1). The basic assembly of these are clearly described by Popovic Larsen (2008).

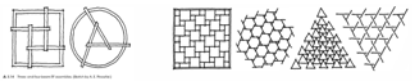


Figure 1. Three and four-beam RF and RF morphology (Larsen 2008).

A reciprocal frame structure can also be constructed from identical or non-identical basic elements as long as a tessellation pattern exists (Kohlhammer & Kotnik 2011). One can argue that where linear materials in these assemblies are replaced by 2D shapes, design opportunities arise with the introduction of the size and nature of the shapes

2.1. PLANAR RECIPROCAL FRAME STRUCTURES

Planar RF in this paper is understood as having the kind of structure that uses planar shapes in an RF assembly in place of linear elements such as rods, beams and bars. To avoid confusion, it is important to point out that the term 'planar RF' had also been used by Popovic Larsen (2008) as referring to those that are used as planar grillage on a 2D plan, such as the flooring of Mill Creek Public Housing Project by Louis Kahn. This paper means the use of planar materials when referring to 'Planar RF'.

In planar RF, the sizing of the members - their depth - is an external parameter (Puyol 2015). The few examples of planar RF structures include the Coca Cola Beatbox Pavilion by Khan and Ohrstedt in 2012 for the London Olympics and the Serpentine Gallery Pavilion 2005 by Siza and de Moura with Balmond (figure 2). The boards informed on the overall pavilion aesthetics.



Figure 2. Beatbox Pavilion panels (left); Serpentine Gallery 2005 panels.

Baverel and Pugnale (2013) have presented a first attempt at classifying the use of planar materials in an RF assembly. The Serpentine Gallery 2005 was classified as 'Thick Elongated Elements' where the boards are treated the same way as rods and bars.

2.2. CUSTOM SHAPE RECIPROCAL FRAME STRUCTURES

Another design opportunity arises when an irregular 2D shape is used in an RF assembly. In 2013, we developed a structure called Euphonious Mobius where the basic principle of RF is adopted using an irregular 2D shape that would result in an abstraction of the Mobius strip or form (figure 3). In effect the 2D custom shapes were assembled as a spaceframe. The outcome was a self-supporting complex form where the connection events allow the components to transmit traction and compression forces. It would generally classify as 'Planar Elements as Part of a Truss' if one would categorise it according to Bavarel and Pugnale's planar RF classification (2013).



Figure 3. Euphonious Mobius (Araullo 2013).

2.3. CONNECTION JOINTS

Like linear RF, due to irregularities of local conditions at intersection events in these planar RF examples, connection of all members often presents a whole new design undertaking for which off-the-shelf fasteners prove insufficient. To analyse the two examples given above: in the Coca-Cola Beatbox project lightweight panels were braced against each other to stabilize the system. The bracing itself required customisation. The Serpentine Gallery 2005 used the mortise and tenon jointing but ensured that all members are of the same size so the mortise and tenon could be typical throughout. In the case of Euphonious Mobius, the use of industrial strength cable ties was a quick solution to ensure slight movement was maintained between the 10mm acrylic panels which enabled the structure to be non-static however free-standing. A connection joint using cable ties is naturally not ideal but it demonstrates the importance of the connection joint in RF structures. To conclude: in order to achieve irregularity and structural efficiencies in RF assemblies, connection technique is the key to ensuring they perform as a viable architectural typology, potentially for end use and beyond exhibition purposes.

Following the background on RF structures and the overview of Planar RF, the paper will present and discuss a project that took findings from the custom shape RF structures and connection techniques into consideration.

3. Ptolemi

Commissioned by Destination NSW, Ptolemi is a site-specific installation for exhibition at Vivid Sydney 2016, located in Campbell's Cove, The Rocks. Ptolemi was developed as a semi-permanent deployable exhibition piece and subsequently, the multi-unit planar timber RF were redeployed for exhibition at the University of New South Wales, exposed to the elements for a six-month period. Here it withstood extreme weather conditions bearing over 100km high winds and severe rain falls.

3.1. PTOLEMI DESIGN PRINCIPLES

Based on a multi-unit quadrilateral RF system, the design is a set of curved wall structures with sloping grid producing irregular and unique components. The highest point of the slope measures four meters, the lowest is one meter, curved to form a half circle with a diameter of nearly 6 meters (figure 4).

Exterior plywood panels are layered with 0.8mm stainless steel in mirror finish, similarly locked in place through notches of intersecting plywood panels, therefore required no adhesives or fasteners.

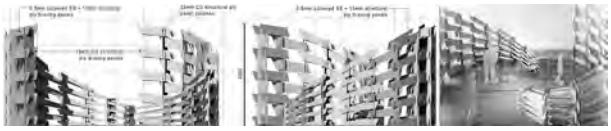


Figure 4. PTOLEMi - Elevations and prototype.

A reciprocal configuration was made on plan, ie. the thickness of the walls is determined by the number of quad units arranged along the width (figure 5). In this case, single units were arranged along the curvature.

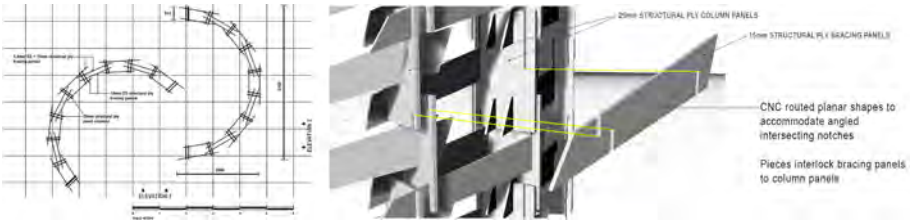


Figure 5. PTOLEMi - Plan; horizontal panels.

Using planar materials, boards arranged vertically resulted with a parametric value in height. This allowed for a reciprocal configuration to be observed on elevation as well. To test the efficiency and performance of this system, no added fasteners were used only a simple notched joint.

3.2. PROJECT LIMITATIONS

There were challenges in ensuring the project met exhibition criteria. The project must comply with strict guidelines in occupying and installing on the exhibition space. The Sydney Harbour Foreshore Authority which is the consent authority for site occupation, required the structures be placed onto platforms to avoid damages to the pavement of the licensed area. As well, installation time and the time for bump-out must take no more than one day and must be done within a seven hour period including the installation of embedded LED and sensor technology. We were faced with challenges in planning and coordinating the manner of build as well as securing the structures onto platforms. The platforms as well became a great consideration. Arup, the engineering team collaborating on the project, required the platforms made of 20mm steel base as appropriate to the sheer scale

and weight of the structures. As well, the Sydney Harbour Foreshore Authority imposed minimal construction activity on the licensed area, which made coordinating all the panels for assembly on site not possible. Under all these conditions, the structures required off-site assembly and brought on site in a near complete state. The structures had to be secured onto the 20mm base plate and delivered via a hiab crane truck.

3.3. ENGINEERING AND NOTCHES

The structural design for the notches was critical in resisting vertical and lateral forces throughout crane activity, road travel within a 10km distance as well as placement on site and performance throughout the public exhibition. The site experienced gale force damaging winds as well as heavy rains and flooding during the exhibition on Campbell's Cove, The Rocks. Again structural performance was tested in these conditions as the structures remained intact but for minor damage to embedded technology. The CNC routed panels consist of 15mm structural ply for the horizontally arranged panels along the elevation (bracing panels), and 25mm structural ply for the vertically arranged panels in between (column panels). They are connected via a simple notched joint.

3.3.1. Asymmetrical Notches

In this assembly the traditional principles of halved joint and notch joint are explored for design and structural purposes. In a digital workflow the line of intersection between two panels which is the contact length (c) is halved to produce the size of the notch (n), also common in traditional carpentry, (d) being total depth of panel (figure 6). In linear RF assembly, the vertical spacing of the centrelines of rods at the intersection point called eccentricity (e) is an important parameter in constructing RF (Larsen 2008; Rizzuto & Larsen 2010).

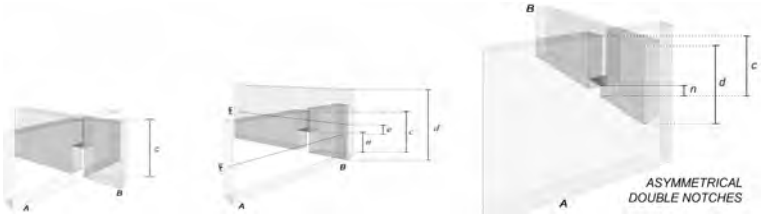


Figure 6. a) Halved Joint, e=0; b) Halved Joint, e>0; c) Asymmetrical double notched joint.

Studies by Garcia Puyol with the object of mass customisation use a digital workflow that considers the contact length, the eccentricity, total depth of panel and depth at centreline, where the eccentricity and the depth of the panels define the depth of the notch (Puyol 2015). As well, this workflow results in shape adjustment of the panels in order to meet structural criteria.

However, for this project, the panel shapes must be maintained for aesthetic ambition. The underlying geometry is discretised into an irregular quad grid producing panels positioned horizontally intersecting with vertical panels. In addition

to the approach described above we looked at the manner of defining the size of the notches for each panel. To keep the panels in a specific reciprocal configuration, an approach to notching must be central in the process to ensure structural efficiencies.

3.3.2. Digital Design Workflow

In this top-down approach, the digital design workflow computationally forces the position of each panel into this RF configuration. Joint design and management can become complex due to the heterogeneous nature of this elaborate jointing. To avoid much reduction in the panel depth which can weaken panel performance, a hierarchical approach to notching was introduced in the workflow. As the profiles of horizontal panels must be maintained for aesthetic purposes, notches for horizontal panels were first calculated according to engineering details (figure 7). Horizontal panels become primary.

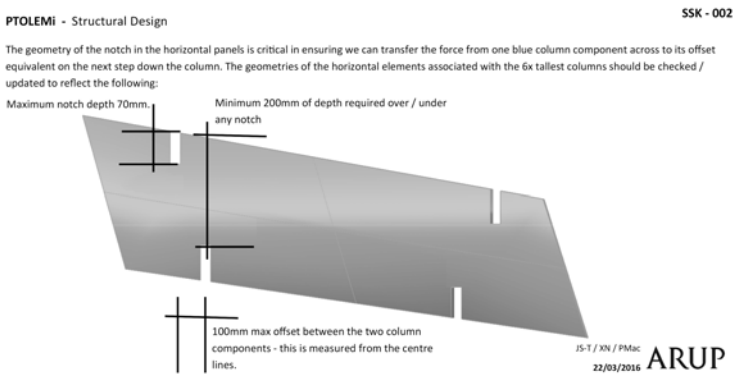


Figure 7. Horizontal panel notches.

In the digital workflow, 1) intersection events were identified; 2) notching uses a sifting process that calculates the total depth of panel along the contact axis. Based on using 15mm ply, panels with a depth of 210-270mm along the contact axis, the minimum 200mm under or over a notch to the edge of the panel must apply (figure 7). Greater depth along the contact axis, will have a maximum 70mm notch at that intersection. Panel depth with less than 210mm along the contact axis, will remove one quarter of its depth to form the notch.

Secondly vertical panels (figure 8) using specified 25mm structural plywood were analysed. The load paths through the structure mean that the loads in each panel vary. Those closest to the base will tend to have the largest axial forces.

In the digital workflow, adjustments to the vertical panels to meet engineering criteria were made, 1) Intersection events were identified; 2) Notching calculated the depth of the panel along the contact axis, the depth of the panel from the top of the notch of the intersecting panel along the contact axis which becomes the size of the notch; 3) The positions and heights of the horizontal panels were adjusted within the reciprocal configuration to ensure the minimum 200mm panel depth ap-

plied over and under any notch. In this process, asymmetrical conditions resulted in corresponding double notches (figure 9).

To ensure the structure is secured onto the base to withstand loads identified previously, the topmost vertical panel at every column is anchored to the 20mm steel plate with a 16mm threaded steel bar lightly tensioned (figure 8). The bottommost vertical panels were secured onto the 20mm steel base plate.

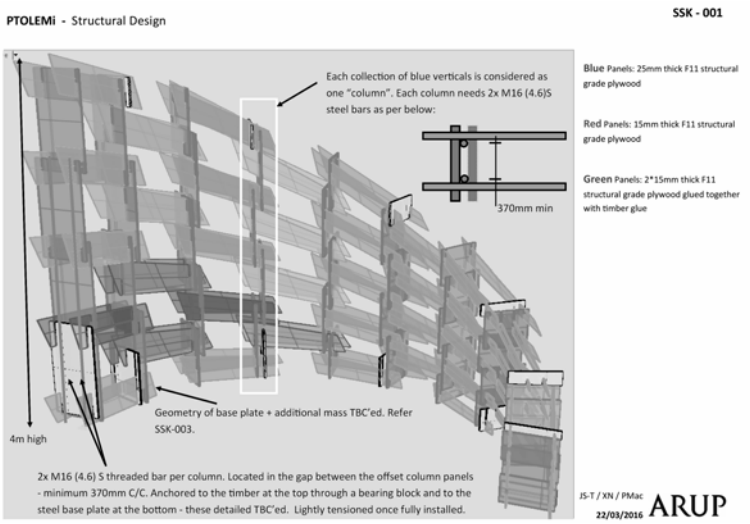


Figure 8. Structural detail.



Figure 9. Ptolemi (Araullo 2016) - Timber planar reciprocal frame structure.

3.4. DESIGN OPPORTUNITIES

Due to its parametric nature we are able to control porosity, position and angles of panels. We also adjusted panel sizes to economise on material usage. As well, we introduced a steel layer for facade aesthetics. In the same way, the 0.8 mm steel sheeting in mirror finish was layered on to the timber panels without any bonding agents and placed with the corresponding timber panel to be locked in place (figure

10). Taking into consideration any timber warping, the notches carrying the steel layers were computationally adjusted for tolerance.



Figure 10. Ptolemi (Araullo 2016) - Layered stainless steel mirror-finish planar RF.

3.5. EVALUATION

Like a large puzzle, the assembly of this planar RF was achieved in a four hour period. Self-registration, digital fabrication processes and equipment bring a level of simplicity to the production of a complex structure. The condition of whether panel 1 lies under or above panel 2 (Parigi & Kirkegaard 2012) is such a great consideration in an RF assembly. Auspiciously, in planar RF this condition results in design possibilities as evidenced herein. Although the intention was in-situ DIY assembly, building off-site gave us new challenges in transporting sections of a reciprocal framework. In the six month exhibition, timber warping was not evident and the structure appeared stable (climbed onto by university students). The steel layer remained intact but for the lower steel panels that suffered as corners were easily bent whilst not bonded to the timber panels. The digital workflow included an iterative process in the design and production of the notches to meet engineering requirements. Adjusting notches meant we maintained the profiles of the panels to meet efficiencies. Depending on the torsional stiffness of the joints/panels, they could be designed separately and without considering the eccentricity between their centrelines. If there is very little resistance to torsion or if the axial force in the panels is very small then the eccentricity can be ignored. However, as there was hardly any “give” in the joint to twisting and as significant axial force in the panels was expected then eccentricity had to be taken into account. As the panels

interact, the load path through the structure to the base meant that the loads in each panel varied which required computational management of the notching. In the digital workflow, the asymmetrical condition of the double notches meant we were able to nominate primary members in a commonly non-hierarchical system regardless whether they lie under or above secondary members.

4. Conclusion

Design possibilities present itself in the nature and size of the planar panels. Where the issue of economy and availability are central, planar RF's efficient use of small pieces of material to produce large structures can be most beneficial for deployable modular and rapidly assembled structures. As a sustainable solution, RF is reliant on issues and limits of serviceability. Therefore, further research should be encouraged to bring planar RF from research labs to end use as an inclusive DIY contemporary architectural typology. Planar reciprocal frame assembly as a potential efficient structure or facade system is an exciting area of research that can lead to economic benefits and can provide a viable solution in today's society.

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THE OTHER DIGITAL

What is the Glitch in Architecture?

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Abstract. This paper will discuss and investigate the issues with the concept of 'glitch' in architecture. There are currently two definitions that sit in a symbiotic relationship with each other; Moradi's (2004) and Menkman's (2011). This paper will explore the implications of these two approaches, while investigating the possibility of a third, unique definition (the encoded transform), and what effect they have on the possibility for a 'glitch architecture'. The paper will then focus on the glitches' capacity to be disruptive within the design process. In the context of architecture, it has been previously argued that the inclusion of glitches within a design process can easily create a process that does not 'converge' to a desired design outcome, but instead shifts haphazardly within a set of family resemblances (Austin & Perin 2015). Further to this, it will be revealed that this 'divergent' quality of glitches is due to the encoded nature of architectural production.

Keywords. Glitch aesthetics; Theory; Algorithmic Design; Process.

1. Introduction

The term 'glitch', and what it has come to represent within digital culture, forces the term to be an umbrella for all sorts of digital, electrical and new-media artefacts which may or may not be at odds with the intended *meaning* of the word. Although there are pre-existing definitions that function effectively within the scope of scientific and artistic analysis, these definitions are problematic for more design-oriented disciplines such as architecture.

The value of such a discussion is two fold. Firstly, it allows for a new method of understanding and critiquing architectural production. For example, the processes of Peter Eisenmann's *House Series* along with the architectural implications of !Mediengruppe Bitnik's *H3333333k* both represent two disjunctive forms of architecture that relate to glitches in their approach. Secondly, and also the focus of

this paper, it opens up *new* methods of working within architecture. As stated previously, glitches within the design process can easily generate methodologies that do not *converge* to the designer's desired outcome (Austin & Perin 2015, pp. 831-834). Instead the glitch offers a disruption to the process and shifts haphazardly within a set of family resemblances.

Thus this paper will conclude with an exploration of 'glitch' techniques that have the capacity to be disruptive to architectural production and investigate the issues around them.

2. Definitions of Glitch and their Problems

From a scientific standpoint, a 'glitch' is an unexpected spike in an electrical current (Wakerly 2006, p. 224) or the phenomena of an algorithm behaving in a way that is unexpected to either the programmer or the viewer (Moradi 2009, p. 8; Scott 2009, p. 20). At first glance this appears to be a pragmatic and useable definition. For example, if a simple logic-gate circuit or algorithm returns the incorrect response, clearly something that objectively resembles a glitch has occurred. This naïve-scientific approach has two serious flaws. Firstly, electrical systems are rarely simple enough to check if a glitch has objectively occurred without specialist knowledge and skills. Secondly, the word 'unexpected' implies a relativist-subjectivity to the term. In other words, it is possible for a viewer to proclaim that a glitch has occurred within a system that the engineer or programmer has set up to work in *exactly* that way. The glitch thus embodies a more complex techno-social relationship than merely an objective state of error and is indefinable within only an objective-scientific framework.

The unavailability of a clear-cut objective approach to understanding what the glitch *is* has lead to artistic practices, under the guise of 'glitch art', to develop subjective approaches to understanding what constitutes glitch.

The first of these approaches, devised by Moradi (2004, pp. 28-32) attempts to attribute *features* to glitch artefacts. In other words glitches *look like* glitches. Moradi points out that:

- Defining its visual characteristics now would probably serve as a 'record.' to map its evolution or to document an appreciation arising from a drive towards its extinction as other more interesting and powerful visualization technologies are invent. (Moradi 2004, p. 71)

Any aesthetic features that can be attributed to the glitch are bound to the technology that houses them. As technology changes, the features that identify a glitch must change with it. Moradi's (2004) approach leads to a definition that is forever requiring revision; the definition is in constant flux. Nevertheless, the features that Moradi (2004, pp. 28-32) offers, namely *fragmentation*, *linearity*, *horizontality* and to a lesser extent *complexity*, have been consistent features in the production of glitch art over the past decade.

In contrast, the second of these approaches, offered by Menkman (2011), attempts to attribute a phenomenological character to the glitch; Menkman (2011, p. 31) calls this character 'the glitch moment(um)'. For Menkman (2011), a glitch

is the embracement of the subjectivity of the viewer. The unexpected behavior of technology that prevents an objective-scientific definition is embraced as the core feature of what constitutes a glitch. The techno-social context of a glitch's occurrence is fundamental to its identification. A glitch, within this framework, is a break from a pre-established pattern being presented to the viewer or user of the technology in question. Menkman explains:

- Through the distorted images and behaviors of machinic outputs, the viewer is thrown into a more risky realm of image and non-image, meaning and non-meaning, truth and interpretation. The machine no longer behaves in the way the technology was supposed to...Though at first the viewer reacts with shock and perceives the experience as a loss, the glitch cannot be subdued as a solid state of perception. Just as the understanding of a glitch changes once it is named, so does the notion of transparency or systemic equilibrium supposedly damaged by the glitch itself. The 'original' experience of rupture is moved beyond its sublime moment(um) and vanishes into a realm of new conditions. The glitch has become a new mode; and its previous uncanny encounter has become to register as an ephemeral, personal experience of a machine. (Menkman 2011, p. 31)

Within this context, glitches and their synthetic counterparts - otherwise known as 'glitch-alikes' (Moradi 2004, pp. 8-11) or 'domesticated glitches' (Menkman 2011, p. 55) - are impractical to tell apart. Things that merely look like glitches based on either their attributed aesthetic features and/or techno-social context can be indiscernible from '*real*' glitches.

These approaches to defining what constitutes a glitch have held up within digital-art practice as the final glitch artefact is rarely removed or abstracted from its original techno-social context; glitch art is more often then not viewed on monitors. However, when this is done, for example Ed Grant's oil paintings of his glitch art, problems arise as aesthetic attributes that would otherwise be discernable as 'digital artefacts' become merely elements of abstraction (Austin 2015).

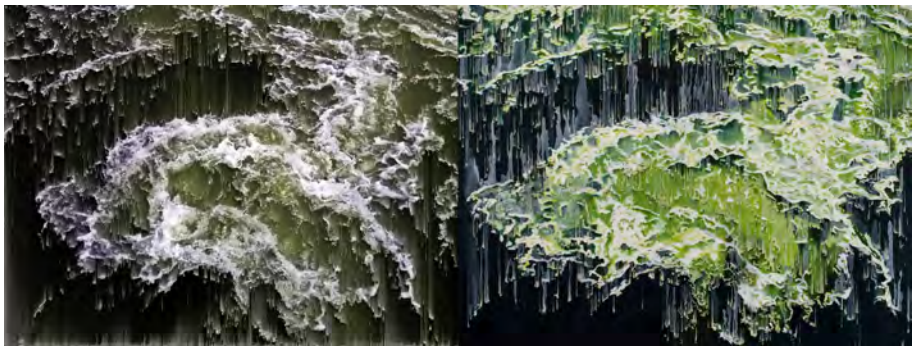


Figure 1. Ed Grant's 'Churn' as both a digital pixel-sorted image and as a oil painting. Reproduced with the permission of the artist.

Although this is a minute point in the context of art, within the context of architectural production, the translation from digital media to physical artefact is common. Glitches within built architecture risk being enveloped within other architectural ideologies. Just as abstraction can encase glitch art when it shifts media, deconstruction and post-modernism can just as easily encase glitch architecture. Although it may eventually prove inevitable that glitch becomes a new wave of these movements, it is in this author's opinion that it should not be accepted uncritically.

3. Glitches in Architecture and the H3333333k Approach

It is common in art to *stretch* the notion of glitch to encompass analogous systems. For example, a genetic mutation or the failure of a building is often referred to as a 'natural' glitch. The use of analogy should be viewed with caution as it strips the term 'glitch' of whatever specificity it may entail to make it absolutely synonymous with 'errors' and 'mistakes'. The glitch, unlike mere error, is embedded purely within electrical systems; its use outside this context is always analogous.

Just as Figure 1 highlights the electrical-dependent nature of glitch art, !Mediengruppe Bitnik's *H3333333k* highlights the same problems within the context of architecture (Austin 2015). The façade was designed by taking a photograph of the existing façade of the *House of Electronic Arts Basel* (*HeK*), data bending the JPEG compressed photograph (i.e. editing the image through its textual representation) and then reconfiguring the original façade to resemble the data-bent photograph (Weisskopf & Smoijo 2015).

The problems this project reveals are two:

Firstly, it is clear that the architecture is being deformed to *resemble* the data-bent image. That is, the façade is designed to produce a photograph that is similar to the data-bent photograph used in the production of the façade. In this sense the semiotic disruption of architectural elements becomes analogous of a glitch in order to render the effect that the building has been data-bent. However, the building, unlike its image, is not a JPEG. The resultant building merely renders the *illusion* of a digital artefact by folding - in a Deluzian sense - the flat-digital viewport of the monitor onto non-digital space, thus giving the illusion of a glitched architecture. The problem is that this folding is not overtly novel or unique in respect to the glitch; it is merely another novel image rendered through anamorphic projection similar to the works of Felice Varini.

Secondly, although the resultant transforms from this process disrupt the semiotics of the architectural elements, the process is severely limited in its capacity to make *spatial* transformations. Architecture is inevitably tied to space and thus transformations of it. To further compound the issue of the glitch's buildability, architecture is consumed in a very different way from images. Not only are there infinite viewpoints of *H333333k* in which the illusion is not rendered, but there is also an inhabitable space behind the façade, which has not been, for lack of a better term, 'glitched'. The problem here is that a two-dimensional image can only represent a very limited amount of spatial information and that architecture is usually communicated with a very large amount of two-dimensional images.

For the glitch to have a novel spatial-potential within architecture its value lies in the production of architecture not necessarily as a direct visual gimmick. Although at first it may seem oxymoronic to have a glitch architecture that does not necessarily render glitches into its built form, the potential design space of such an approach is not only much more open, but capable of dealing with more complex spatial design intent. It is worth noting that the glitch in glitch art is still a process-oriented approach, the only difference is that these glitch artists work directly on the final artefact while architects work purely on representations of that said artifact (Evans 1997, p. 156).

4. The Encoded Transformation

Design objects are not necessarily artworks. The consequences of such a distinction are important. Artworks are justified metaphysically to the artefact in question; it is given meaning and *aboutness* via its *causal history*. (Danto 1981). In other words the mode of production gives qualities and value that may not be embedded within the final artefact. In contrast, design objects, such as architecture, commonly do not have meaning and instead justify their processes via the artefact itself with notions of functionalism and 'good design' (Dilworth 2004). Design objects thus commonly do not have meaning. The difference between art and design causes problems for Architecture to apply glitch aesthetics in the same methodologies as art practice.

As highlighted previously, the term 'glitch' is not easily defined. Both Moradi's (2004) and Menkman's (2011) approaches look at the glitch through the lens of aesthetics - which in the case of Menkman (2011) is contextually based.

As a drastic departure from these notions of definition, I would like to investigate the causal history of the digital artefacts these definitions hope to describe. The value of such an approach is the shift in understanding. Rather than a 'glitch' being understood via its aesthetic properties, it can be understood as a *process* or *technique*.

Glitches, whether synthetic or real, purport to be moments where instead of technology creating the illusion of transparency, allowing us to look through the display device directly into the model or image, the glitch is the moment where the technology embeds itself onto the display devices, thus breaking the illusion (Menkman 2011, p. 30).

This 'illusion' of transparency is embedded in all modes of communication as highlighted by Shannon's Model (Shannon, 1948). Information is encoded from a humanistic form of communication, for example images, into a non-humanistic form to be stored and/or transmitted, and then decoded back into the humanistic form when required.

The advantage of digital technologies specifically is that once information is stored it is still mutable. This gives rise to two types of algorithmic transformations. The first, and most familiar, are '*pre-encoded* transforms'. These transforms operate on what the information represents. For example, image filters go to great algorithmic lengths to manipulate the linear sequence of characters on the computer drive that represents the image in order to produce the desired effect. The

second type of transform is the '*encoded* transform'. These transforms act with no regard of what the information represents. For example, rather than using an image filter an image may be distorted by manipulating its binary, hexi-decimal or ASCII representations. Encoded transforms operate upon the information and thus not what the information represents leads the formal outcomes of such processes unpredictable.

The conceptual importance of this distinction between pre-encoded and encoded transforms is that the encoded transform embeds within it all glitch processes. All glitches, whether natural or synthetic are born through an encoded transformation of some sort with the exception of individuals using pre-coded transforms with the intent of producing a glitch aesthetic.

As previously argued the difference between these two algorithmic approaches via highlighting pre-coded transforms, in other words traditional-architectural algorithmic approaches, are likely 'convergent' within the design process while encoded transforms, and thus glitches, are 'divergent':

- Glitching, however, takes small variations within the ASCII, hex or binary textual representation of an image to create vastly divergent formal arrangements. Every step in the glitching process generates an uncontrollable and unpredictable result, forcing the designer to procedurally move sideways as they evaluate unexpected outcomes. Glitch aesthetics demands the designer adopts new design reasoning. The convergence of algorithmic processes involves an active interplay be-tween code and designer, whilst the glitch-alike requires the designer to be reactive. Unlike 'Processing's' 'convergent' outcomes, the core difference and, therefore, potential of glitch aesthetics lies with its capacity to generate 'divergent outcomes'. (Austin & Perin 2015, p. 832)

This author, therefore, provides a definitive explanation of what constitutes 'glitching'. 'Glitching' is *any* approach that seeks to drive outcomes via transformation of encoded information with no regard for its meaning. In contrast, the algorithmic processes used within architectural production are traditionally concerned with the meaning of the information to make informed and authored design moves.

5. Approaches to Glitch Architecture

Artists are free to deal with the perception of glitch architecture through its distortion as a graphic image such as !Mediengruppe Bitnik's *H3333333k* and the architectural-focused collages of Oliver Ratsi (2011). These processes are dependent upon the architecture already existing to give rise to these effects. It is however, possible for the final model to be glitched or a render to be glitched and remodeled. However, unlike artists, architects inevitably deal with not only the spatial consequences of such images, but also pragmatic and functional concerns. In this sense, for the glitch to be practical, there is likely to be a further design phase to deal with these issues as glitch artefacts have no explicit strategic or formal architectural ambition embedded within them.

In a digital-design context, an encoded transformation requires a computer file to transform. In the context of architectural production, two types of file-format types dominate the production process; two-dimensional images and three-

dimensional models. It has been highlighted previously that the increased complexity of a 3D modelling file makes it impractical to successfully execute an encoded transformation while leaving the file operable (Austin & Perin 2015, p. 835). The work of Mark Klink, shown in figure 2, shows the successful process of such an encoded process when it is exhibited. A glitched .OBJ will *always* offer the same formal features; parts of the figure will be distorted and become 'pointy' in the same way.



Figure 2. Mark Klink's 'Lucy01' and 'Lucy03'. Reproduced with the permission of the artist. .

The two-dimensional image has more creative potential than the OBJ for three major reasons. Firstly, image files are easily translatable into different types of image files; for example a .PSD can easily be changed to a .JPG. Secondly, image files can easily be translated into different media and back again; for example an image being turned into sound and back again through a .RAW extension being opened in Audacity. Finally, the set of possible families (Kipnis 2008, pp.197-201) is much larger as not only does every file format offer a different family (figure 3), but some degree of image-analysis algorithm is required to translate these glitches into three-dimensional spatial form; thus multiplying the number of possible families. Therefore the potential of the two-dimensional image within a design context thus dwarfs that of the OBJ.

Each of the images within Figure 3 are generated through a variation of file formats with differing degrees of distortion to the original figure of the drawing. In some instances the encoded transform, destroys any resemblance to the original figure, while in others only slight distortions are maintained. Nevertheless, each image has its own creative potential to be used in the production of architectural space. Glitch techniques thus embed a series of new challenges for architectural production. Just as the 'stopping problem' presented a problem for time-based processes for digital architecture in the 1990s the glitch proposes the 'starting problem'. With what glitched material is it appropriate to *start* translating into spatial expression? The consequences of this problem are not yet clear within architec-

tural production. To highlight the difference in approaches, Austin & Perin (2015, p 835) focus on a process that starts with glitching a planar drawing, while Haslop et al. (2016) investigate a system that invests itself in glitches of an old Motorola phone.



Figure 3. A range of glitch data bends operating upon the same architectural plan.

6. Conclusion

Architecture proposes unique and novel hurdles for the embedding of glitch aesthetics within its discipline. It asks questions of glitch aesthetics in which artistic practice has not invested itself. The glitch in architecture delivers two very important realisations. Firstly, within architecture glitching is more practically understood as a method of production (i.e. the encoded transform) than as an aesthetic style. And secondly, inevitably it must be synthesized through algorithms and architectural intent to be spatialised.

Within artistic practice the glitch has over time become formal in the sense that the glitch is inherently outcome-oriented. In other words, the gesture of the glitch is inevitably attached to the aesthetic qualities of the artwork. Although the glitch cab be formal in architecture, it may also have the potential to be formative (i.e. process-oriented). An architect's design process is glitched and re-resolved into a spatial system which may then be glitched again; these acts of glitching are not design moves themselves but mechanisms to resist the convergence of the architect's design process opening them up from the normative and predictable behaviours of the algorithms upon which architectural production is now built. In

turn architecture offers the capacity to understand glitch aesthetics as parts in a larger whole, rather than as an effect that is applied to the information at the last moment for aesthetic or conceptual merit.

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DIGITAL TOOLS, ANALOGUE MINDS

A Project-based Framework for Understanding the Dialogue In-between

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Abstract. This paper is situated in a specific research by design setting, where the realised work of architecture has been generated with digital tools operated by analogue minds of designers. It examines the relation- ship between the two entities, the designer and the tools, in an attempt to understand their specific roles better, trusting that this can lead to anew ways of enhancing the design process. Through revisiting the processes, methods, techniques and tools employed within various design-cycles of the project, authors present their own /designerly/ experience, pointing to both the potentials and limitations of the digital tools used. The attention is drawn to the importance for a human designer to have a critical awareness of the true nature of the computational systems and the capacity of both to adapt to the given context, in order to be able to embrace them and use to their full potentials.

Keywords. Project-based learning; design exploration; digital tools; design cognition; low-cost conditions.

1. Introduction

In the professional context of the contemporary architectural design practice digital tools have become widely trusted modes for supporting the design process in all of its phases. Designers and engineers nowadays extensively operate within the digital realm, relying on computers primarily as design generating engines, as tools for exploration of design ideas and their testing, and as means of communication and efficient data transfer to all other active participants in the design chain. The name computer aided design itself suggests that computational systems are to be regarded as complementary to designer led process, assisting a human designer in conducting the actual design thinking and design production. To what extent

a computer has the capacity to aid the designer, and what would be a degree of its autonomy within that process are some of the concerns raised and addressed within this paper.

Founded on the theoretical grounds that have already given recognition to designer's perceptual and cognitive abilities as the keystones in the generative processes of creating innovative design solutions, whereas the generative role of the digital techniques is accomplished through the designer's simultaneous interpretation and manipulation (Kolarevic 2004), this paper explores further the relationship between the two in a project-based setting. It aims to identify aspects and areas of the design process in which the use of particular digital tools might play the most prominent role in complementing and assisting human designer's design thinking and actuation.



Figure 1. 2D and 3D representation from the winning competition entry: a wireframe perspective drawing of the proposed market design and the site plan of the proposal showing the rotunda in the middle of the market and the alley of trees within the market area.

The paper presents a newly built and recently put in use Central Green Market project designed by the authors during the period of 2012-2013 and finally realised in 2015 (RAUM, 2015). By exposing their particular *designerly* experience during the creation of the Central Green Market, authors intent to demonstrate the level of compatibility of the computational design methods with the cognitive and perceptual design approaches within various design stages. The paper focuses on the initial, exploratory stage of the design and only briefly informs about the later stages of the design that are concerned with its technical resolution, leaving these to be tackled in the future. However, this paper wants to make explicit that despite the fact BIM was not an option for this particular project, the supporting role of the available digital tools was essential in the formation of design knowledge, in enabling collaborative thinking, and design development until its very completion.

2. Project's Background

After winning a local competition authors were commissioned to complete all phases of the design, from the initial design conception to the final design with technical details and site supervision provided. The design task: to redesign and extend the existing Central Green Market (within a total area of 14000 m²) in Negotin - a small town in East Serbia was conditioned to be low-budget given that this is one of the poorest regions of Serbia. The old market was in a poor condition itself, with many of the existing structures in devastated condition, ready to be demolished.

In a given context, with a limited building technology available and insufficiently skilled construction workforce, the preservation of the old building was estimated to be unfeasible. The restrained budget allowed for only a few of the existing structures to be preserved, including the alley of large sycamore trees and the rotunda in the middle of the market place (figure 1), both of which authors planned to incorporate into a new design, as the key identity features of the place.

3. From Modular to Parametric

From the very beginning and throughout the whole design-span of the project the digital tools were employed to drive the process. An array of software applications were used for design exploration and inquiry (Rhino, Grasshopper), for creating 2D and 3D representations (Rhino, Sketchup, CAD, Adobe applications), for design detailing (CAD, Rhino and others) and for the interactive communication with the engineers and other participants in design chain.



Figure 2. 3D sketches created with an open-source software – Sketchup, and the use of Adobe applications for postproduction. The main purpose of representing the initial design idea, and sketching out the market atmosphere.

Based on the market stand space requirement analysis and the analysis of circulation of people and goods, a mathematical pattern of 11m‘ x 11m’ was defined to be applied at the main market area and the above canopies. Through the further steps of the design exploration the set primary modular unit was modified and adapted to the more specific requirements of the project (figure 3).

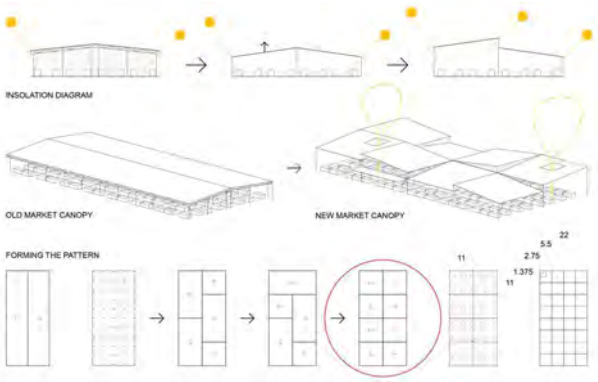


Figure 3. Basic concept for the main market area with the modular patter 11m’x11m’, and with the fragmentation and modification study.

4. Parametric Aid to Design Exploration

The pattern found its application in the functional organisation of the green market, and even more directly in the design of the market canopies. This was especially important given the specific microclimate of the Negotin region characterised with high temperature fluctuations during the year, but also with the highest number of bright days (88 day in average) and the longest sunshine duration in the country (Smailagic et al 2013). Thus, the canopy structure had to be designed so that it provides both sufficient light and shading during the hot summers, while being able to protect the market space and its users from the elements - rain and snow during the winter months. The existing canopy, a simple double pitched roof, was covering the whole market space and provided insufficient insolation (figure 3).

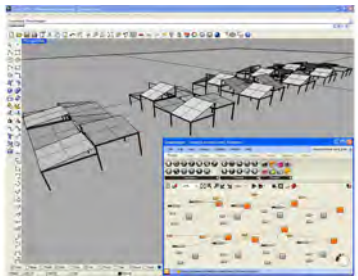


Figure 4. A simple algorithmic schema for the canopy geometry manipulation in Grasshopper.

Authors used Rhino for quick 3d sketches and formal tests, and complementary parametric application (i.e. Grasshopper) for creating a number of possible canopy's geometric behaviours that could vary in fragmentation and roof inclination. The roof dynamics had to comply with the requirements for the protection against the elements, to appropriate the direction of the rain water away from the market stand areas, in a way that all market stands are well sun lit (figure 4). For this purpose authors have created a simple algorithm for geometric manipulation to take place within a parametric modelling space (i.e. Grasshopper for Rhino). This simple schema assisted the process significantly in terms of generating a large number of iterations and variant solutions to be discussed and evaluated.

5. Parametric Designerly Experience

Now, if we are to identify the approaches that characterise the exploratory stage of the design process of the Central Green Market in Negotin, we would need first to note that authors have operated (almost) exclusively in a digital realm, exploring the potentiality of variant geometric behaviours parametrically. However, before starting off with parametric exploration, based on their previous experiences with parametric modelling, authors recognise the necessity to create an algorithm with a high degree of explicitness. The necessity to do so has been advocated by many long before. Knuth, for example states that algorithm must be based on precisely defined steps and that following actions must explicitly be specified for each case (Knuth 1997). In other words, designer's intention and deliberation play a central

role in parametric modelling.

Therefore, a designer needs to have a predefined notion of what is being explored and to which (parametric) extent - i.e. when shall the parametric exploration rest for the human designers' cognitive perceptual capacity to intervene and complement it. The limited complexity of the algorithm used for the canopy geometry exploration and its manipulation in Grasshopper (figure 4) should also be seen in that light. Moreover, it has been evidenced that an excessive number of parameters in the schema can easily lead to the non-manageable design solution spaces. In this scenario, a number of design variants would grow exponentially and pose a challenge to both human designer's cognition, and just the same to the computational system (Bittermann 2011). Many point that an excessive complexity of the schema could easily hinder the process and encumber the process of evaluation of each design variant due to the restrictions in time and in other resources (Kilian 2006; Turrin et al. 2011).

Research shows that designers who have managed to overcome complex design situations with success use an approach often referred to as a designerly way (Cross 2001; Buxton 2007; Moggridge 2007). In the case of the Central Green Market project, the explicitness of the algorithm and the limited complexity of its schema made it possible for designers to discuss, evaluate and compare a number of variant solutions at a relatively early stage of design exploration, and thus to establish a cognitive methodological designerly approach to design, and grasp its systemic nature timely. The relevance of understanding the systemic nature of design has been brought to light by Stolterman who sees it as an iterative process of inquiry that moves between the whole and its parts: "...a rational designer works on many alternative designs in parallel in an iterative way, while going back and forth between the whole and the details. This way of doing design is not a choice. It is at the core of what it means to act in a rational, disciplined, designerly way" (Stolterman 2008).

Thus, the use of parametric tools at this stage has provided designers with a perspective that is of value for design thinking in at least two respects. Firstly, it bound them to clearly identify distinct issues in the given context and define the evaluation criteria prior to the parametric exploration. The design problem is not given - it is framed within the first stages of the design exploration and inquiry, within the framing and naming stages (Schön 1983). Secondly, through attentive articulation of all geometric elements with consideration of their correlated, interdependent conditions, the use of parametric tools also allowed for a more systemic approach to design to happen.

One could argue that similar values may have been achieved by the means of an analogue approach. But authors had reasons to believe that many of the challenges that emerge at this stage, that one could identify as wicked problems (Rittel and Webber 1973), would be impossible to address in such a systemic way. One of the reasons is that the analogue approach could only offer a limited number of iterated formal outcomes and try-outs to study, discuss and evaluate. This lack of bases for design exploration and inquiry to happen could only result in its incompleteness. Other reasons have to do with the efficiency of the process, as the attempts to explore the design potentials through iterations in analogue terms would entail a

human designer to start the process all over again.

The low-cost conditions of the context made an impact on the choice of software - much of them were licence free or open source (Sketchup, Grasshopper etc). However, designers relied on their competencies to appropriate the tools they had for developing the techniques they found necessary for operating this specific project. Aided by the selection of digital tools authors have explored a full range of resources available in the given design situation, including their knowledge and embodied skills in order to develop a project specific design strategy, or situating strategy as termed fittingly by Gedenryd. The role of digital tools was to assist the authors to go beyond the intramental (i.e., in the mind) design activities undertaken for accomplishment of the intended design idea (Gedenryd 1998).

Even though the digital tools available for the Central Green market project were rather basic in this design stage they have clearly supported the designers in: understanding the present situation (1), exploring potential futures (2), expressing designers‘ vision of the potential future concepts (3) and evaluating which course to take in the design (4). In another scenario, without the parametric tool at hand, a limited number of design variants would inevitably constrain designers' perceptual-cognitive capacity, imposing on the designers rather basic design concepts that have a little chance to develop into well informed and mature design proposal.

6. Digitally Design Communicates

As pointed by Akin, design consists of a series of representations to designer's mind, and to the minds of designer's collaborators, clients and others because, as he explains: "the mind has its own internal representations in order to communicate through external representations." (Akin 1982). Likewise, at the following stages of design's technical resolution and detailing it was important that external representation conveys the design idea and information that addresses various scales, levels, and scopes of technical resolution.

It was essential to employ tools and techniques that allow an efficient transfer of all relevant design data to, at this point, an extended list of collaborators (mechanical, electrical, plumbing, fire protection, and structural engineers, consultants for waterproofing, roofing, glazing, material suppliers, clients, etc.) that called for explicitness and clarity in how the design is communicated.

The designers worked with detailed 3D models as a method for communicating the tectonic idea most explicitly to the engineers (and all others in the design chain) to calculate, optimise or propose an alternative, and send information back to designers (figure 5).



Figure 5. Detailed 3D models made in Rhino; tectonic resolution by architects in 3D on a level of a structural details – rainwater gutters incorporated in structural system (middle), complex joint of 8 beams supported by 1 column (right).



Figure 6. Photo records from the building site – structural details resolved by the architects in 3D now realised. Images show two cases of complex joints with 8 beams supported by 1 column. .

This also allowed for a high level of precision to be achieved that has particularly proven to be the invaluable in the final, construction stage (figure 8; figure 9). Moreover, it allowed for a few very specific design/structure/construction issues to be resolved efficiently, to name just the two: 1.detailing of the structural joint with 8 steel beams leaning on 1 column at the same height (figure 5; figure 6), 2. detailing of the canopy segments that were to be designed with sycamore trees growing through (figure 8).

Should be said that the method of construction - prefabrication was deliberately chosen, as authors trusted it would support the tectonic logic of the design most explicitly and would leave little room for miscalculations. Given that all steel structural elements were prefabricated, then transported from another part of the country to the building site to be erected and bolted there the tolerance for potential deviations in the production and construction was minimal, as any error in the data transfer to the production line would result in a series of mismatch on the site and hinder the realisation of the whole project.

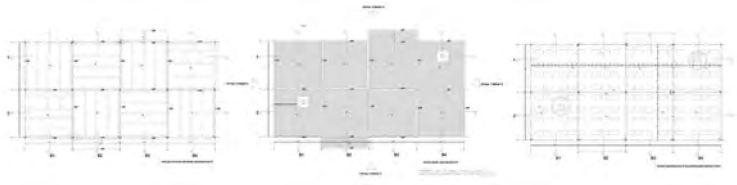


Figure 7. Plan of the steel structural grid of the canopy.

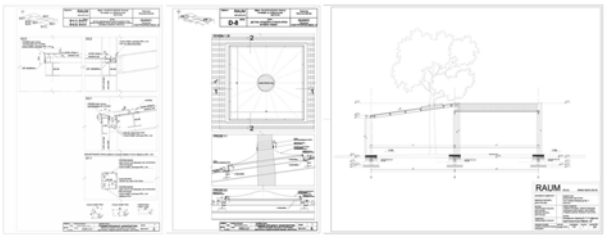


Figure 8. 2D drawings of architectonic and tectonic details; detailed resolution of the joints of structural steel elements and the rainwater gutters (left image); detailing the canopy segment designed to let the sycamore tree to grow through.

To conclude, this particular *designerly* experience of using 3D digital models for architecture/construction collaborative thinking, design resolution and detailing speaks obviously in a support of the BIM software application, and could be seen as a naïve version of it.

Even though BIM was not an option, the making of a highly precise 3D digital models proved to be important in the formation of design knowledge and its sharing, and especially invaluable asset for the construction, as it has directly informed the production and the erection of all steel elements without any welding that resulted in a deviation of a mere 2-4 mm per 11000 mm span (figure 9; figure 10).



Figure 9. Scenes from the building site – assembling and bolting of the steel structural elements.



Figure 10. Scenes from the building site – erection and bolting of the steel structural elements.

It enabled faster production of structural elements, shorter completion time and finally the reduction of the overall costs. Moreover, it helped to keep the authors/architects fundamentally involved in the all stages of the design process, and to be in control of it.

7. Conclusion: Analogue Mind - a Creative Drive

Who designs? This question posed by Terzidis when referring to the parametric design method as a possible alternative to a human designer (Terzidis 2003) has found many opponents, perhaps for the obvious reasons. Scheurer for instance formulates his argument against this idea of potential dehumanisation of the design process in four points: computers as we know them are deterministic, not creative (1), tools don't find solutions, solutions produce tools (2), simulations are never as real as the real thing (3), computers will never be fast enough (4) (Scheurer 2013). His argumentation places a designer in a central position of the process, because as he explains further: "when we move on from designing buildings to designing algorithms that design buildings, we are just changing the level of abstraction, but not the level of responsibility" (Scheurer 2013). The fear of neglecting human

cognitive abilities in the design processes has been expressed before. McCullough for instance advocates for taking more pride in human abilities and calls for making of: "an inevitable technological change in a more human-centric direction." (McCullough 1996).

The authors/designers of the Central Green market and the project itself, benefited from the support of the digital tools in the execution of the design in all of its stages. Parametric modelling facilitated the addressing of the questions of design in relation to geometric articulation and in that respect contributed to the expansion of authors' cognitive and perceptual abilities. On the other hand, it also confronted the authors with a number of challenges, such as the necessity to externalise all relevant conceptual parameters and formulate them algorithmically in an explicit manner. By having a clear situating strategy, i.e. by defining the scope of parametric inquiry that authors have closely related to the geometric performance of the canopy structure, and by having a clear design intention, authors have managed to meet this challenge.

In making the conclusion of what are to be the contributions of this particular *designerly* experience, authors recall Schön's views of design as an iterative process of reflection-action activities that he saw as essential for the formation and the development of new knowledge (Schön 1983), but also his precedent Dewey's view of an interactive and experiential learning that he referred to as a project-based learning (Knoll 1997). Likewise, the Central Green Market should be seen as an opportunity for a project-based learning, as it has been perceived and experienced by its authors throughout the process of its design and execution.

Finally, the concluding lesson that this paper wishes to transmit is that digital tools, even when quite limited and conditioned with a low-cost working environment, fundamentally support designers' involvement in the process, from helping designers' cognitive abilities expand, to sustaining designers' control over the process until its very final stages. In this particular *designerly* experience, due to the limited digital tools at hand, designers were set straight in the centre of the process that was for that reason precisely evermore integral and connected.



Figure 11. The Central Green market completed and in use.

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A PRODUCTIVE AMBIGUITY:

Diffraction Aberrations as a Template for the Architectural Surface

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Abstract. The hi-resolution imaging of public urban space for both promotional and surveillance purposes is now undertaken by a range of ubiquitous visioning technology such as Internet webcams, drones (UAV's) and high-altitude aircraft cameras. The ability to control and manipulate these types of images is a growing concern in an increasingly 'envisioned' environment. One approach is to disrupt or modify the 'emission signatures' of urban surfaces, which requires an understanding of the digital algorithms used to assemble and transmit image content into grids of visual data. Recent scaled tests show that Fraunhofer diffraction algorithms can interfere with the smooth transmission of image data. When these algorithmic patterns are physically constructed into a building façade, they create natural disruption glitches in the camera's successful transmission of visual data. The paper details how the quantum of visual aberration in the digital portrayal of the city can be determined by algorithm-based façade patterning.

Keywords. Surveillance; camoufleur; envisioned; algorithms; diffraction; façades; aberration.

1. Introduction

Internet webcams, camera drones (UAV's) and high-altitude aircraft cameras now produce hi-resolution imaging of urban space for a range of promotional and surveillance applications. From the camera-shy industrialist to the military camoufleur, the ability to control and manipulate these types of images has become the preeminent concern of an increasingly 'envisioned' environment. Central to the viewed target's 'bag of tricks' therefore is the ability to exploit techniques by which to disrupt or modify the unwanted 'emission signatures' from a building to overhead observation. The enhanced effectiveness of any intervention in these transmissions must involve methods by which to modify the multispectral signature production of the image, the rapid deployment of the technology and low cost of the deployment of these systems.

One approach to this type of technological intervention involves the use of diffraction or lens flare algorithms to interfere with the smooth transmission of image data. Recent scaled tests show that when these algorithmic patterns are physically constructed into a building façade they create procedural glitches that disrupt the camera's successful transmission of visual data. This not only ensures that the ambiguity of the target remains intact across the global digital image platform, but in so doing, it transforms a perceived 'flaw in the system' into a productive tool.

Glitch, from the Middle-High German glitschen: 'to slip', is becoming a more widespread phenomenon in a media-dominated world. Commonly defined as a brief fault within an electronic system, it is now emerging as a discrete digital art movement that '...explores imperfection by producing or saving unwanted images.' (Joachim 2005). This subtly worded distinction between 'producing' and 'saving' is, however, crucial to the determination of the glitch's conversion into a productive architectural tool. By drawing upon the notion of the pure glitch 'the result of a Malfunction or Error' rather than the glitch-alike '(to) produce and create the environment that is required to invoke a glitch and anticipate one to happen' (Moradi 2004), any architectural application of the diffraction effect is immediately endowed with all of the unexplored properties and potential effects of the electromagnetic spectrum. Put simply, it is precisely because the Fraunhofer diffraction effect is a naturally occurring phenomenon, that its application is not delimited by artificial constructs or facsimiles.

Using the results obtained from recently conducted scaled tests, the paper will therefore show how the translation of different Fraunhofer diffraction patterns into architectural surfaces can operate as disruptive camouflage patterns to camera reception. These new prototypical camera responses demonstrate how orchestrated façades can be strategically designed to create precise modifications to the way in which a digital camera receives and disseminates visual data. Erroneously termed 'impediments' to digital production, the paper will detail the precise conditions and parameters by which façade can be designed to magnify the degree of visual aberration in the camera's reception of a building. The ultimate point of this discussion will be to demonstrate that these patterns provide a broad range of productive ambiguities and opportunities for the designer to intercede in the digital portrayal of the city.

2. The Camera View: Between Concealment and Surveillance

In her work on the scale and levels of pixel data within the satellite image, Laura Kurgan (2013) reveals how image intensity and contrast data can be precisely indexed to situated events (figure 1). The pervasive time-lapse recording of the planet by a French SPOT satellite imaging system reveals images of mass war graves in Kosovo in 1999. In this scenario, each pixel has an address expressed in longitude and latitude that corresponds with a unique location, and each reveals the heat value of that place at the time the image. With this type of pervasive aerial scrutiny operating and with a camera resolution of a single pixel equaling 10 square metres, there is little opportunity for data to remain undisclosed.



Figure 1. Satellite images showing (left) no graves present and (right) evidence of a massacre and a disturbed grave in Izbica, Kosovo, 1999, taken at an altitude of 822 kilometres.

As terrorist activities become a growing global concern, defence-related camouflage tactics are increasingly concerned with the broader surveillant capabilities of foreign target acquisition systems. Military-based research to date has led to the development of highly complex, cumbersome techniques that require the generation of live 'counter-data' (Kitson et al 2016), but to make land facilities invisible in remote combat locations. However, security-related operational centres are increasingly situated in dense urban zones, thus introducing a need to disrupt or diminish the data content transmitted to unwanted multi-spectral reconnaissance from UAV's and high-altitude aircraft cameras.

Past research on camouflage tactics at a built scale has focused on the painted application of pixelated patterns to military buildings (Larson 2013; Robinson 2012; Baušys & Danaitis 2010). In these cases, camouflage is only operational within a narrow band of the electromagnetic spectrum visible to the human eye. More recent military approaches to building camouflage now incorporate tactics that attempt to respond to either space-based or airborne hyperspectral imaging technologies that capture both spatial and spectral (infrared) information (Kitson et al. 2016; Snaper 2006; Manolakis et al. 2003; Reynolds & Kinsella 2002). Yet these techniques remain highly complex and cumbersome, requiring the generation of 'counter-data' for invisibility (Kitson et al. 2016), or to put it simply, they produce a different camouflage for different backgrounds. Consequently, effective camouflage needs to satisfy a broader range of requirements that includes the capacity to produce a spectral match to multispectral or hyperspectral remote-sensing instruments as well as less technical infrastructure and low cost (Blake 2007; Shaw & Burke 2003).

In a completely different arena, the highly competitive car industry has developed a means of concealing its latest features. Entitled "Brick" camouflage, Ford has produced vinyl camouflage stickers, which are "uniquely" applied to each vehicle to disrupt the ability to distinguish new exterior features in sunlight, both by human perception and by camera. Tailored to multiple environments, the patterns are designed to disrupt the integrity of the vehicle's shape, surfaces and colour by delaying the brain's recognition ability (figure 2). While easily deployed and low-cost, the functionality of this solution is nevertheless limited to only a narrow band of the visual spectrum.



Figure 2. Ford test track camouflage.

3. Glitch: 'pure' or 'alike'

While delineating a contextual understanding of the perceived and real effects of cyberterrorism, Peter Krapp draws a clear distinction between its perceived and real effects, or in other words, between authenticity and artifice.

'To take the real threats of cyberterrorism seriously is certainly not alarmist, but it is irresponsible not to distinguish between a Net sit-in and the failure of an ATM network, between conceptual Net art and attacks on a hospital generator...' (Krapp 2011)

Krapp dismisses the bulk of 'hacktivism' as the minor, impotent resistances to existing government and private network systems. These attacks exploit 'the processing rhythms of certain system resources' and 'are nothing more or less than digital demonstrations' (Krapp 2011 p. 51).

The recent emergence of the electronic glitch as a digital art phenomenon presents an interesting parallel to Krapp's words. Glitch artist Tony Scott's website instructs users in one of either two ways: 'Wait for something to go wrong, or force something to go wrong if you're a busy full-time glitch professional' (Scott). The conversion of the accidental into the deliberate does indeed produce examples of complex network 'errors' that seemingly have immense aesthetic appeal. However, the 'forced' glitch, unlike the accidental or pure glitch, is the product of direct intervention and, in that respect, it does not belong to an indexical system. Because it is the facsimile of an aberration or error and therefore theoretically not repeatable, it cannot populate itself by drawing upon a repository of naturally occurring variations of itself. In this respect, while being unique it is also limited - it is another version of a 'digital demonstration' (Krapp 2011 p. 51). Diffraction, on the other hand, is a naturally occurring and repetitive phenomenon within the vast system of optical science. The distinction here is that diffraction is a naturally-occurring error between two independent systems that, in this case, are deliberately rather than accidentally brought together. There is no human intervention within the error process itself. Furthermore, the field of optical science invokes a vast array of diffraction effects when brought into play with the camera mechanism that are quantifiable and able to be endlessly repeated.

4. Fraunhofer Diffraction and the Aberrations of Digital Technology

Diffraction occurs throughout the camera's aperture range when a beam of light is partially blocked and split by an obstacle commonly known as a diffraction or transmission grating and, in this respect, it is part of a know indexical system. Diffraction gratings cover the ultraviolet, visible and infrared spectra (Palmer 1995). The presence of these visual aberrations in captured camera data, while known, cannot be controlled and they occur regularly as a result of different climatic conditions, such as rain or fog (figure 3). Fraunhofer diffraction is formed by internal diffraction on the image sensor mechanism of the camera when the scattered light falling on the sensor exceeds the range of luminance that can be accurately measured by this mechanism. (McCann 2007) Camera response functions are tuned to perform in low-contrast, uniformly illuminated scenes specifically to avoid an optical overload or what is known as 'glare spread function' (McCann & Rizzi 2007). However, despite manufacturers' attempts to control the image-making process and product, these aspects of the camera's function acting in conjunction with light remain unpredictable and uncontrollable.



Figure 3. Fog acting as a diffraction grating on a building façade. (This image is available at: http://www.sharenator.com /Some_Cool_Pictures/).

5. Disruptive Surfaces

A series of practical tests were designed to investigate how far-field diffraction grating patterns, or Fraunhofer patterns, as one of the known effects of optical science, could be deliberately used to disrupt camera protocols. The patterns were selected from digital image-processing procedures algorithms with the ultimate intention of constructing a façade based on selected pattern at a magnified scale. This would force light falling onto the camera's image sensor mechanism to scatter and make it behave like a diffraction grating. It is worth noting again note

here that unlike the 'forced' glitch whose construct is a single or 'one-off' facsimile of a network error, this instead deliberately draws upon a naturally occurring and repeatable collision between the system of optics and the camera mechanism. A further objective of the tests was to observe the effect of the 'mirrored' grating patterns in conjunction with the f-stop increments of the camera. This would potentially provide a vast array of interrelated effects for an architectural surface, which could be deliberately calculated and applied by referencing the data obtained in the test.

Five Fraunhofer patterns were selected. Three were derived from the camera's internal data-scanning or raster-scanning procedure, a fourth was based on the Human Visual System (HVS) comprising hexagonal elements (Deering 2005), and a fifth, random non-digital pattern was used based on the randomly generated type referred to by Cantoni et al (2011) (figure 4). The Fraunhofer patterns were created using the open-source software *Fresnel Diffraction Explorer* and a Fast Fourier Transform algorithm. The tests were conducted using a Sony SX43E Handycam digital video recorder, comparable to the Kintronics long range IR PTZ surveillance camera (2014). Both cameras have CCD sensors, which use interlaced scanning, and both have a zoom capacity of 60x.

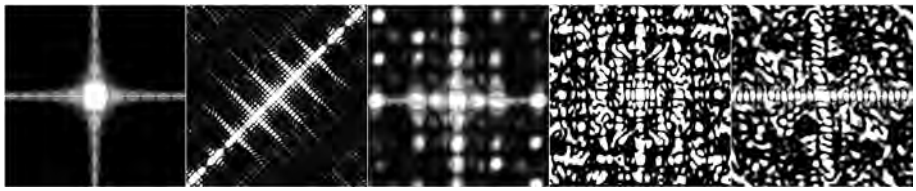


Figure 4. Left to right: Standard horizontal raster scan-order pattern; Standard horizontal raster scan-order pattern in a 45˚ rotated orientation; Recursive Z scan-order pattern; Hexagonal, HVS-based pattern; Random or non-periodic pattern.

The diffraction gratings were cut from 2mm opaque black acrylic squares and then placed individually in front of an American DJ FS-1000 Followspot with a ZB-HX600, 120V 300W halogen lamp to simulate the building light emission conditions that would operate at night within an urban context. The camera was placed at two different distances from the image plane: 8 metres and 5 metres. The light source was located directly behind the image plane at a distance of 0.5m. This represents a scaled approximation of the standard Internet camera viewing distance from a brightly lit image source where a relative scale of 1:10 operates, i.e., the 8m image plane distance in the test correlates with an 80m distance in an exterior environment, and so on. Similarly, the grating elements used were 500mm2, correlating with a typical building façade element of 5m2. The aim of this was to enable specific features of the recorded image to be tabulated in accordance with the camera's aperture range or f-stop increments acting in conjunction with its zoom trajectory.The results of the individual patterns were processed using *ImageJ* and *HyperCube2* analysis tools. *ImageJ* analysis was used to assess both the number of unique colours produced and the luminosity emission of each pattern. Because the objective was to see the effects of the diffraction grating upon the

camera's image-processing function, the quantum of unique colours produced by each grating along with the luminosity (brightness) of each was critical to the assessment of the amount of disruption to the camera. Accordingly, for each grating pattern, the image at the high end of the camera's aperture or f-stop range was selected to observe the number of diffraction artefacts present (the number of unique colours being directly linked to the effects of diffraction), because this is the point at which these are most likely to occur. *HyperCube2* was used to provide the static and dynamic display of the image cube and to determine the hyperspectral effects of the patterns.

6. Test Results

The tests showed that digital-based Fraunhofer diffraction patterns deliver extremely strong brightness artefacts that become more exaggerated as the camera zoom factor increases. Of these, the Fraunhofer pattern derived from the horizontal raster scan-order pattern in a 45˚-rotated orientation produced the highest number of diffraction artefacts. This was evident in by the number of unique colours that each of these diffraction patterns produced as seen in the *ImageJ* montage in figure 5, the addition of all images within the inward and outward zoom trajectory of the camera. Other digital-based Fraunhofer patterns also produced significantly more brightness artefacts than non-digital patterns.

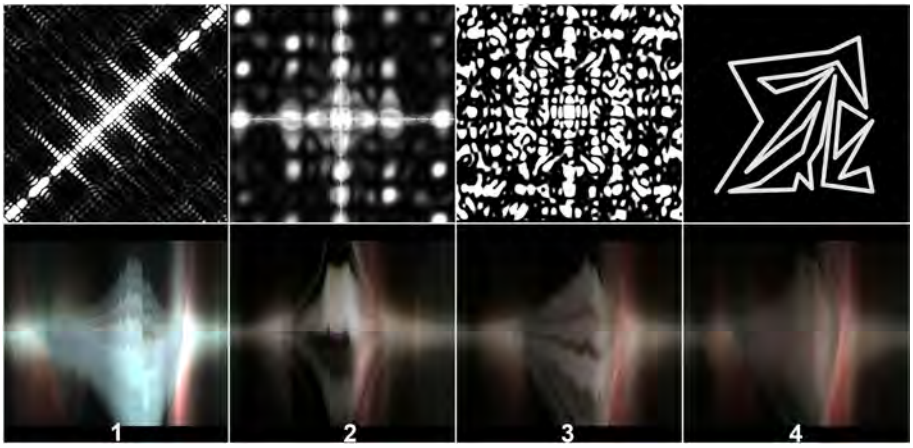


Figure 5. ImageJ test images showing the total disruptive effect (the sum of all images in the camera trajectory) of digital diffraction patterns (images 1-3) upon camera reception over a range of different camera apertures. Image 4 on the right demonstrates the lesser disruptive effect of a non-digital pattern.

HyperCube2 tests showed the hyperspectral effects of the Fraunhofer patterns. Figure 6 below shows the high level of camera interference produced by the use of this pattern as a hypothetical building surface. The tests showed that the use of a magnified Fräunhofer diffraction pattern as a perforated screen, backlit and attached to a building surface, can transform it into a diffraction grating screen that radically modifies image legibility across multiple spectra.

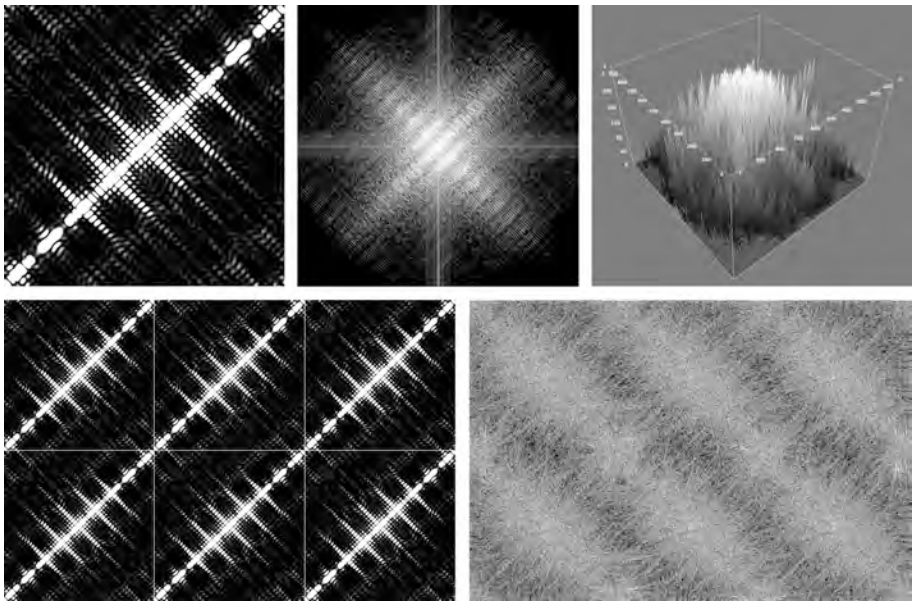


Figure 6. Top left: Fraunhofer pattern extrapolated from a digital raster pattern; Top centre: Fourier transform of pattern from HyperCube2 showing power spectrum of the embedded image using log compression and the high amplitude of the frequencies comprising the image; Top right: ImageJ 3D visualisation of the pattern's luminance surface plot showing extremely high levels of emissivity. Bottom left: Montage of Fraunhofer pattern assembled as a modular array for a building surface.Bottom right: The proposed effect of this array upon camera reception calculated using HyperCube2 software.

Materialised as a series of modular, milled or routed screens covering the entire building surface, these super-sized diffraction grating patterns are a cost-effective way in which to disrupt the clean transmission of visual data. The patterns can be manufactured as a system of 1m2 detachable units, which can be cheaply manufactured and easily assembled into arrays for any building surface. As modular units, they are also easily flat-packed and transported to any location (figure 7).

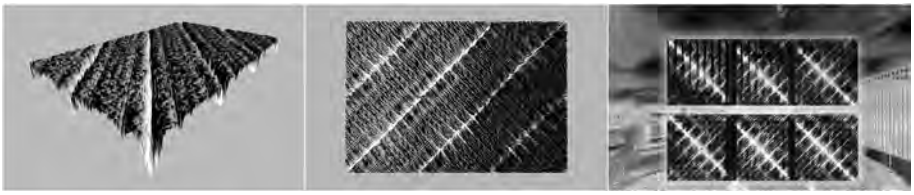


Figure 7. Left to right: Fraunhofer pattern extrapolated from a digital raster pattern transformed into a modular screen; assembled screen seen in elevation; hypothetical application of screens to a building surface.

7. Conclusion

The reconsideration of the glitch within an architectural field thus raises issues of productivity and agency. Its transformation from a perceived 'systemic flaw' to a productive architectural tool is possible when it derives its complexity and diversity from the interaction between two independent systems, one electronic and the other of applied mathematics. In this respect, the applied effects of Fraünhofer diffraction allow the designer to draw upon an endless array of physical possibilities.The tests show how new prototypical camera responses open the opportunity to configure façades to orchestrate a natural collision between an existing physical system and the way in which a digital camera receives and disseminates visual data. By showing how the physical application of these patterns can be customized to suit the specific camouflage requirements of any context, they reveal that a building's programmatic activity can be comprehensively masked according to an endless array of possibilities. The specific intention to magnify the degree of visual aberration in the camera's reception of a building thus aligns this work with a newfound agency that, by reinforcing the ambiguous, allows the designer to continue to intercede in the digital portrayal of the city.

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COGNITION AND EVALUATION OF ARCHITECTURE ENVIRONMENTS BASED ON GEOMETRIC CONTOUR REFERENCES AND AESTHETIC JUDGEMENTS

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Abstract. This paper presents the outline and the achieved results of an experimental study developed to understand the differences on how close architecture spaces with distinct geometric characteristics at contour level, including rounded, curvilinear and sharp, rectilinear elements, are perceived and evaluated. In order to do so, eighteen virtual reality architecture spaces were evaluated by thirty-two test-subjects according to like/dislike aesthetic judgments. As expected, the tested subjects showed a higher level of preference for spaces with rounded, curvilinear contour elements. On another way, when the level of space curvature was high, considering the whole space surface and not only the contour of plan transitions, the level of preference decreased significantly. These results support the idea that rounded, curvilinear elements are interpreted as being more pleasant and preferred than sharp, rectilinear ones and create new knowledge on the how the levels of such preference are more accurate for moderate rather than radical curvature rates.

Keywords. Geometric contour; Architecture space environment; Curve, rounded, angular and rectilinear; aesthetic judgement; experimental study.

1. Introduction

Automate building technologies gave rise to a whole new era of the discipline of architecture. The facts that: (i) Digital Revolution has been increasingly effecting

the architecture field, namely the achieved closeness between prototype and mass production techniques, that; (ii) recent studies have develop work and theories on how curve, rounded and angular, rectilinear contour objects have the ability to trigger specific pleasant or unpleasant cognitive processes on humans and that; (iii) we believe to be of the outmost importance to understand architecture, which are its limits, what it has to offer and how it can better assist our conscious and unconscious needs and feelings; demand an update and clarifying exercise on the potentialities of the architecture of today.

That said, as a field that seeks the knowledge about beauty and taste, aesthetics have been under the scope of thinkers since at least the Greek Classical Period. However, the way we used to examine "real matter of fact (Hume 1757) would change considerably in the late 19th century when Gustav Fechner tries to understand subjective judgments through methods of extreme ranks. He later introduces the notion of median as a mean of formal analysis of data, jumps into the field of experimental aesthetics and elaborates on the pleasing condition of aesthetic objects (Heidelberg). At this point the study of aesthetics begins to stand apart from subjective reasoning to getting closer to a more objective evaluation.

Future work on the 20th century would perform experimental studies on angularity (Lundholm 1921) and curvature (Poffenberger et al.) and on subjective preferences on lines, forms, colors and shapes (Gordon 1909; Valentine 1962; Silvia et al. 2009).

With the arrival of the Digital Revolution a set of innovative tools would become available to measure beauty at a completely different level. More than ever the study of subjects in general was closer to an objective and quantitative point of view rather than a more subjective, fallible and less accurate one (Hume 1757). Techniques like low and high space frequency (Bar et al. 2007) and biosensing technologies such as hearth beat, electrodermal response and electroencephalography opened a whole new era on the definition, perception and evaluation of pleasantness, beauty and aesthetics.

Among modern researches on angularity and curvature are studies on car interior design (Leder et al. 2005), real objects and meaningless patterns (Bar et al. 2006, 2007), symmetrical and asymmetrical abstract geometric forms (Silvia et al. 2009), level of curvature evolution through time (Carbon 2010), realistic architecture environments with decorative elements (Vartanian et al. 2013) and virtual reality architectural spaces with distinctive high level geometric natures (Shemesh et al. 2015). Balance (Locker et al. 2002), contrast (Specht 2007), color (Polzella et al. 2005) and geometric orientation (Miller 2007) (Silvia et al. 2009) are other studies developed under these new techniques and technologies with the aim to better understand the way that we perceive and evaluate form either in a conscious or unconscious state.

2. Goals

The goal of this study is to understand and create knowledge on the hypothesis that humans show a higher preference for curved, rounded elements rather than angular, sharp ones. To identify, in a quantitative level, the way that abstract architecture

spaces with different geometric contour natures and distinctive characteristics elements are perceived and the grade of this preference. In order to do so, there will be considered spaces composed by plans, curved surfaces and both elements arranged together. The evaluation of the case studies is to be done according to the basic aesthetic judgment and the approach/avoid decisions that they trigger. This study also aims to verify the existence of a statistical significant correlation between the collected answers on the perceived taste sensation and the attractive judgement on the represented spaces. Ultimately and based on these results, it aims to propose a significant and effective improvement in the process of architecture design.

3. Research Hypothesis and Variables of Study

The primary research question of this study is: Do people find architectural space environments with curved, rounded elements to be more pleasing than architectural space environments with angular, sharp elements?

This study has considered three kinds of variables: Moderating, independent and depended. The (i) moderation variable was gender, divided in male and female; the (ii) independent variables were architectural spaces composed by (1.1) rectilinear surface transitions, (1.2) curvilinear surface transitions, (2.1) non-prominent edges and vertices or derived transitions, (2.2) non-prominent edges and vertices and prominent edges or derived transitions and (2.3) non-prominent edges and vertices and prominent edges and vertices or derived transitions; and finally, the (iii) depended variable was (a) the perceived taste sensation, unfolded by 'like' and 'dislike' aesthetic judgement towards the presented architectural space-images and (b) the response action time.

4. Description of the Architecture Spaces

In order to investigate this proposition, this study counted with 18 architecture space-images. All space-images are derived from the same base: an orthogonal 3-dimensional virtual space with 20 units of length, 5 of width and 3 of height. The other spaces were found through two main levels of transformations: (i) contour geometric evolution and (ii) comprised element complexity. By turn each of these groups include other revolution stages: 6 in the first case and 3 in the second. Contour and geometric changes embrace low feature transformations, as the name states, at a contour and geometric levels:

- Type 1 (for future notice, 'sharp-high') - 90° angle at plan intersection;
- Type 2 (sharp-tight) - 45° angle plan chamfer with a 10cm base radius at plan intersection;
- Type 3 (rounded-tight) - rounded surface with a radius of 10cm at plan intersection;
- Type 4 (sharp-loose) - 45° angle plan chamfer with a 20cm base radius at plan intersection;
- Type 5 (rounded-loose) - rounded surface with a radius of 20cm at plan intersection and finally;
- Type 6 (rounded-high) - a complete transformation from a Euclidian to a non-Euclidian geometric nature at plan intersection. At this level, contour embraces the totality of the space surface.

Element complexity considers high feature transformations:

- Type a (non-prominent) - negative, non-prominent edges or rounded surfaces;
- Type b (rail-prominent) negative, non-prominent and positive, prominent edges or rounded surfaces and;
- Type c (spot-prominent) negative, non-prominent and positive, prominent edges and vertices or rounded surfaces.

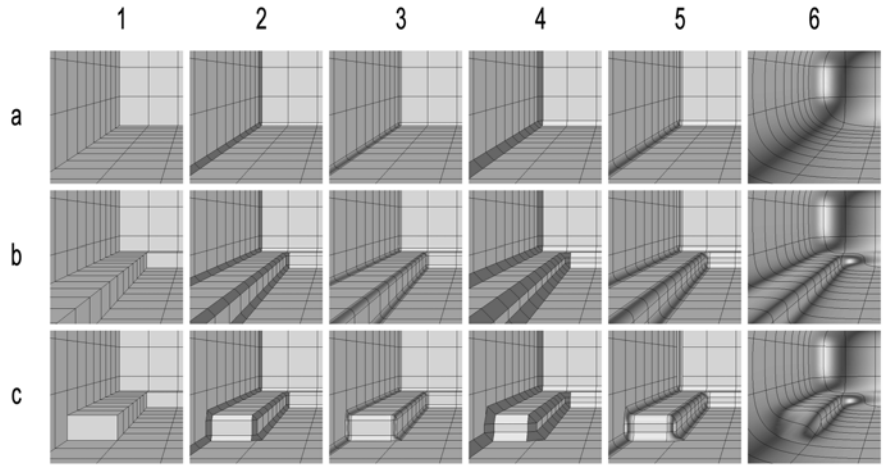


Figure 1. Matrix of the space-images' transformation levels.

As showed in figure 1, this configuration sets up a matrix of 6x3 space-images where the contour geometric evolution and the comprised complexity elements can be studied and analyzed either in a connected or a separately way.

Within the comprised element complexity level (a, b and c), 'sharp-tight' and 'rounded-tight' space-images (for future notice, SI) share a direct correspondence in the way that they are built upon the same controlled variables, including a plan transition of 10cm base radius. The only difference between them is the geometry nature that is applied at the level of plan intersection. In case of 'sharp-tight', a 45° plan chamfer and in the case of 'rounded-tight', a rounded plan transition with Euclidean and non-Euclidean elements. The same applies to 'sharp-loose' and 'rounded-loose SI with the difference that, instead of a 10cm base radius, it is considered a 20cm base radius (figure 2). Such differentiation is included to understand if a significant change in the transition's scale would interfere with the reported level of preference between the same transformation properties.

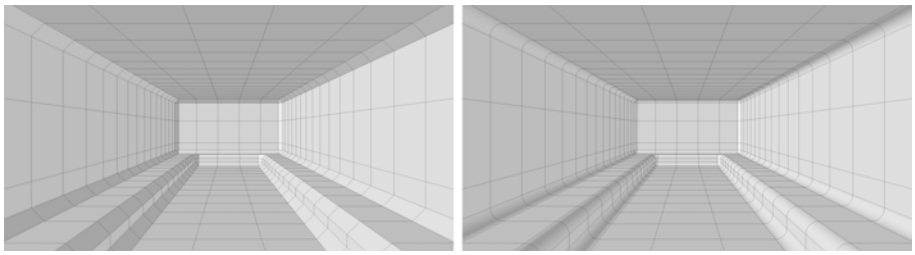


Figure 2. 'sharp-loose' vs 'rounded-loose' space-images.

By another hand, 'sharp-high' and 'rounded-high' SI correspond each other but not in a direct, linear way in the sense that they follow the controlled aforementioned transformation levels but their result is too far apart for a direct correspondence. 'Sharp-high' SI take under consideration 90° plan transitions and are relevant for the study in the way that they are a close analogy to most of the spaces that we build. By doing so, they also tend to fall in the area of the psychological phenomenon of mere-exposure effect (Zajonc 1968). Contrarily, 'rounded-high' space-images represent non-Euclidean geometry spaces, standing apart from most of our built spaces and, by being so "strange" tend to fall in the opposite scope of 'sharp-high'.

The level of information that each space contains was target of deliberately focus attention in order to aim for neutral bias. Despite of the aforementioned elements under examination, all information able to lead to the main object's distraction and sample's infection were abolished. For this reason, all space images appear in tones of gray, without expressive color, texture and additional elements that normally take place in the most simple architecture spaces, such as doors or windows. A simple variation of light was the only parameter that was included due to the fact that it directly interferes with the 3-dimensional perception of the space-images. The observer's height of the space-images was set to 1.675mm, the average height of the Portuguese female and male adult population born between 1971 and 1980 (Garcia 2007), the average born dates of this study´s eligible participant's sample.

5. Experience's Layout

The experience was set upon the group of represented SI to be evaluated by the test-subjects through action-response. In order to assure that each participant went through the same experimental conditions, aiming for a within-subject design, there were constructed 2 sequences of the set of spaces to be presented: a 'regular' sequence, found randomly at www.random.org, and its corresponded inverse order sequence.

To every showed SI, subjects were asked to answer to the stand-alone scenario that they have to choose one from the two available answer-options based on a dichotonic pair: 'like' (I like the presented architecture SI) and 'dislike' (I dislike the presented SI). These action-responses were made through the pressing of 2 gray, identical buttons, with a diameter of 5cm, centered over the computer's keyboard and located over the 'd' and 'return' keys. Each of the 18 space-images were pre-

sented 5 times for a total of 90 space-images in each sequence and were presented for a maximum span time of 3 seconds. The transition between the space-image parameters was made by a neutral gray image with a centered black 'X' and was showed for a variable span time that went from 1.45 to 2.15 seconds.

5.1. STUDY'S SAMPLE

This study has counted with 32 participants. To assure neutral bias in the action-response process participants were divided into 4 groups of 8 test-subjects according to the order that the space-images were presented (first 'regular', then 'inverted' and vice-versa) and the location of the action-response buttons ('like' on the right, 'dislike' on the left and vice-versa). In order to better assist the test-subjects in their action-responses, it was added a gray horizontal bar with a '+' and a '-' symbols at the bottom of each space-image. The position of such symbols pointed the side where 'like' and 'dislike' action-responses should be made: '+' for 'like' and '-' for 'dislike. The sample of participants was divided between 2 geographic areas: a metropolitan city and a peripheral small city.

5.2. PRE-TEST

The experimental stage was preceded by a standard, neutral pre-test. The objective of this pre-test was to prepare the participants for the upcoming decisive phase namely to understand if they were able to follow and control the logic and physical mechanics of the required dichotonic left and right action-responses. In order to do so there were presented 20 parameters for 'like'/'dislike' evaluation, including 3 'like' and 3 'dislike' words to which the participants were asked to answer in accordance.

5.3. TECHNICAL SPECIFICATIONS

For this study it was used a laptop computer for the display and evaluation of the architecture spaces. The specification of this component are: One laptop Computer Intel® Core(TM) i7-4700HQ CPU @ 2.40GHz 2.40GHz processor with 16.0 GB installed memory (RAM), 64-bit Operating System, x64-based processor and an Intel® HD Graphics 4600 and a nVIDIA® GeForce GTX 850M Graphic Card, with a screen resolution of 1920x1080 pixels. Statistical analysis was made through IBM SPSS Statistics, version 22.

5.4. ETHICS PROTOCOL RESEARCH

The Research Protocol of this study has been submitted and approved by the Ethics Committee of ISCTE-IUL.

6. Results

General sample analysis show a preference for rounded over sharp space contour transitions although in small rates due to noise interference. The average of this preference was of 53.98% against 46.02% for 'rounded-tight' and 'sharp-tight' SI and 54.75% against 45.25% for 'rounded-loose' and 'sharp-loose' ones, respectively. ANOVA analysis for these transformation levels show statistical signifi-

cant differences for p-value ≥ 0,064. As expected, there was not found statistical significant correlation between the related 'sharp-high' and 'rounded-high' space-types. This result has probably to do with the aforementioned mere-exposure and strangeness effects. Contrarily to what was expected, there was not found significant differences between the 3 levels of non-prominent and prominent space-types as to the presence of elements with such characteristics. Although it was expected a preference for 'non-prominent' over 'rail-prominent' SI and, by turn, the latter over 'spot-prominent' SI, participants have reported to be more affected by the abstract emptiness of 'non-prominent' SI when in comparison with the more complex composition of the 'rail' and 'spot-prominent' types, declaring a preference of almost identical levels for the last two.

A second analysis was carried considering only the test-subjects that have reported a coherent choice between 'tight' and 'loose' SI either between or among each of the high feature transformation group. The goal of this analysis was to consider only the participants that revealed able to make a distinction between the direct related SI ('sharp/rounded-tight' and 'sharp/rounded-loose'). To be included in this analysis participants had to have reported a preference of at least a 40% variance (a difference of 2 or more 'like' action-responses in the total of 5 times that each SI has been presented) between 2 or more of these groups or at least one preference occurrence equal or over to 60% (difference of 3 or more 'likes'). 13 of the total of 32 test-subjects fulfilled these requirements. A single 40% variance (difference of 2 'likes') and differences of 20% or less (difference of 1 or 0 'likes') in between these groups were considered casual occurrences and led to the participant's exclusion due to the fact that he/she was not able to make a distinction between the direct related space-images and was considered noise. To this last group counted with 19 test-subjects.

Table 1. Comparison of 'like' type response-actions.

	Sharp-tight	Rounded-tight	Sharp-loose	Rounded-loose	Sharp-high	Rounded-high
a	18	31	23	35	20	14
	36.73%	63.27%	39.66%	60.34%	58.82%	41.18%
b	31	49	23	49	18	19
	38.75%	61.25%	31.94%	68.06%	48.65	51.35%
c	21	45	22	39	23	18
	31.82%	68.18%	36.07%	63.93%	56.1%	43.9%

In the consistent-response analysis the related preference related between 'sharp/rounded-tight' and 'sharp/rounded-loose' space images was significantly more expressive. ANOVA analysis over these transformations shows a significance level for p-value ≥ 0,0. The average of this preference was 64.1% against 35.9% for 'rounded-tight' and 'sharp-tight' space-images and 64.4% against 35.6% for 'rounded-loose' and 'sharp-loose' types, respectively, being the highest value of reported preference 68.18%, reflecting a level of preference more than 2 times higher for 'rounded-tight' space-images (45 'likes' against 21 for 'sharp-tight') and the lowest, 60.34%, representing a level of preference of 2/3 and 1/3 for 'rounded-loose' and 'sharp-loose' space-images respectively (table 1). There were

conducted 3 statistical ANOVA analysis methods: Turkey HSD, Scheffé and Bonferroni. This last was included to attend the relatively low eligible participant's sample of this analysis. All 3 tests show a clear preference for 'rounded-tight' over 'sharp-tight' and 'rounded-loose' over 'sharp-loose' SI with corresponding p-values of 0,002 and 0,002 for Tukey HSD, 0,005 and 0,004 for Scheffé and 0,002 and 0,002 for Bonferroni.

Between 'sharp/rounded-high' related images, significance was less expressive, predominating however a preference for SI that enclosure the mere-exposure effect's hypothesis. Within the high feature transformation SI, the 'non-prominent' type was the less preferred, followed by the 'spot-prominent' and lastly, the 'rail-prominent' types.

Due to the fact that data interpretation aimed to more unconscious over conscious responses, such analyses were made to the first of the two presented sequences. Both sequences point nevertheless to the same reported results. It may also matter to refer that, in the process of data analysis it was observed a high discrepancy between the evaluation answers of participants from the metropolitan and the peripheral city areas. Whereas the former's collected data shows a clear distinction rate on the evaluation of the direct-related SI ('sharp/rounded-tight' and 'sharp/rounded-loose'), pointing to a high level of sensitivity and awareness to close low feature transformations, the latter have reported virtually imperceptible differentiation values. These results are considered to be interesting and should be a target of close attention in a near future.

7. Conclusions

Results show a higher level of preference for architecture space environments with rounded, curvilinear contour elements specially when there were reported significant differences between direct related architecture space-images. On another hand, collected data do not point to a preference for complete non-Euclidean geometry spaces. Such result has probably to do with the fact that participants found these spaces to be "strange", something that may be related with an opposite condition of the well documented mere-exposure effect. Space representations with rounded, curvilinear contour elements were then perceived as being more pleasant and preferred than those with sharp, rectilinear ones particularly when moderate rather than radical curvature levels were considered.

8. Future Work

In the attempt to consolidate the results here obtained, this study will be continued under the same basis considering the enlargement of the participant´s sample. To the strengthening of already achieved outcomes, it will be interesting to include a more clear understanding on the hypothesis that geographic related variables may interfere with the level of perception of test-subjects.

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GLITCH SPACE

Experiments on Digital Decay to Remap the Anatomy of Glitch in 3D

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Abstract. This research informs of a series of experimental design practices for the understanding computational glitches in architecture which appears to be equivalently a 'given' as well as an 'informed'. 'Glitch-space' is introduced to navigate the discussion through a spatial interpretation of digital decay. Currently glitches are only explored as forms of 2D art. We however, look to reconnect the underlying data to its digital architectural spatial form. Our methodology a systematic iterative process of transformational change to explore design emergence on the base of computational glitches. A numerical data driven process is explored using decayed files which are turned into 3D formal expressions. In this context, stereoscopic techniques are experimented, helping understand further how glitch can be performed within a 3D virtual environment. Ultimately we explore digital architectural form existing solely in the digital realm that confidently expresses glitch in both its design process and aesthetic outcome. Thus, our research intends to bring a level of authenticity with the notion of 'glitch-space' by discussing 3D interpretations of glitch in an architectural form.

Keywords. Digital Decay; Glitch; Digital Design Methods; Glitch-space; Data Interpretation.

1. Introduction

Glitch works and studies can be categorised through different lenses focusing on its disparate but undisconnected aspects. Some criticise glitch practices for being "no more than a brightly coloured bubble-gum wrapper that doesn't ask for any involvement" (Menkman 2010, 2) and for being not creative enough (Mulder & Spuybroek 2012). Glitch itself is also regarded as a stimulus to questioning

the limits we can reach in digital modelling and the predictability of digital files (Almond 2009; Temkin 2014). Glitch deepens the appreciation of human agency and creativity within the digital realm of architectural design in the way glitch humanises the computer. A glitch acts deep within our technology and comes about seemingly unexpectedly (Shipwright 2015). We can look to digital forensics, file restoration and cultural preservation (Webb & Brown 2016; ibid. 2011; Brown & Webb 2010; Kvan 2016), or we can embrace glitches as a new opportunity for a digital antique (Schnabel et al. 2016; Aydin et al. 2016).

Digital architecture within the digital realm is increasingly as important and resolved as the physical building output. As a physical building sits in our built environment exposed to weathering altering appearance, digital form sits on storage devices exposed to updates altering legibility. This brings us to question how digital architecture decays and what happens to it when it glitches. Similarly, digital decay in the form of glitch is a 'natural' force within the digital realm that creates new interpretations of digital information.

The unique contribution of this research is that it treats glitch in two forms; first as 'the given' and second as 'the in-formed'. In contrast precedent works tend to observe the relation between these two forms in an 'immediacy'. Two glitches are always seen on the same horizon, producing no triumphant hierarchy between each other, which is bounded to a phenomenological deadlock, whereas its subjective capture finds room to grow into static protocols. Therefore, glitch works tend to create monolithic outcome. However, the glitch itself seeks a vertical dimension and an excessive remainder between glitch as 'the given' and glitch as 'the in-formed'. The present work identifies this 'fuzzy' and unexplored part as 'glitch-space' in which its sporadic nature is questioned.

2. Precedent Works

Glitch is currently explored solely in two dimension as an accident rather than a natural occurrence. Glitch can be employed as a system for 3D interpretations. In our research we harness glitch through a spatial architectural interpretation. Previous works looking into glitch effects in 3D space include !Mediengruppe Bitnik's 'The House of Electronic Arts (HEK)' located in Switzerland, Banksy's Ariel mermaid found in his controversial 'Dismaland' and 'Good Vibrations Storage Unit' by Studio Laviani (figure 1).

These samples are less explorative on the inventive role of glitch as an encroachment on the multidimensionality of 3D space than 2D visual disturbance. Their expressions of virtually corrupted images do not interpret glitch as an output that we search as richer meaning within the design method than merely exhibiting a corrupted elevation picture.

A precedent that is responsive to the appreciation of glitch aesthetics is 'The Hackaton' project led by Retsin (2014). The designer's methodology requires a single form to systematically change to develop an unexpected final design outcome. Their design follows a simple method starting with a mesh figure and building upon this original geometry through iterative cloning, mirroring, adjusting and rotating each consequent piece of geometry. This is an additive process that gen-

erates a very unique form (Retsin 2014), adding incentive for further deploying discrete elements such as glitch.



Figure 1. Ariel Mermaid at Dismaland (Jobson 2015), Good Vibrations Storage Unit (Laviani 2014) and House of Electronic Arts Basel (!Mediengruppe Bitnik 2015).

3. Digital Decay

Our design-research recalls glitch as a methodology to design 3D spaces within the digital realm and to advance the interpretation of glitch from 2D expression to 3D interpretation. The architecture remains in the digital realm and therefore remains scale-less leaving the architectural perception of space in the eye of the beholder grounded by their previous spatial experiences. Employing a methodology of transformational change to explore design emergence on the base of glitches or decayed files, (figure 2) the aim is to generate a contemporary architectural interpretation of decayed data (Haslop et al. 2016).

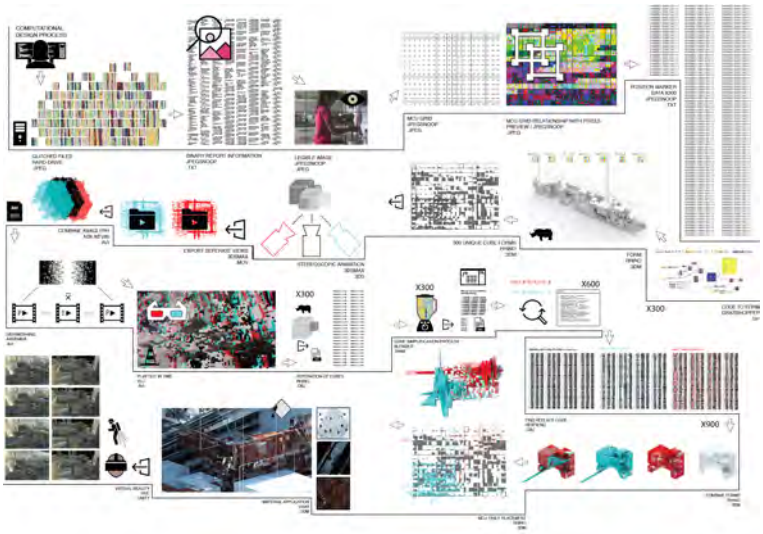


Figure 2. Process of Design Research.

3.1. DATA MANIPULATION IN JPEGSNOOP

A folder of JPEG compressed photographs taken in 2007 remained on a hard-drive storage device for 9 years. There was no editing of their binary code and yet in 2016 these files opened in wild shifts of colours and pixels seemingly completely random and unexplained new glitched perceptions (figure 3).



Figure 3. Glitched JPEG files from 2007 opened in 2016.

The JPEG compressed code does not change over time; it is the computer's 'perception' of this code that shifts. These new interpretations give us rich visual information surrounding natural digital decay rather than forced intentional glitching techniques. The glitched digital files discovered become a starting point to engage in a design through discovery process.

We used both the digital code and the visual interpretation of these files to engage a digital design process employing glitch as a means of generating digital architectural form. We began with *JPEGsnoop*, a freeware developed by Hass (2015) to extract information from one digitally decayed file. The program displays the jpeg compression system of a minimum coded unit grid (MCU grid) overlaid on top of the legible image (figure 4, left). We noticed that there is a direct visual relationship between this gridding system and the way in which the glitched pixels are arranged in the glitch interpretation of the file (figure 4 right).

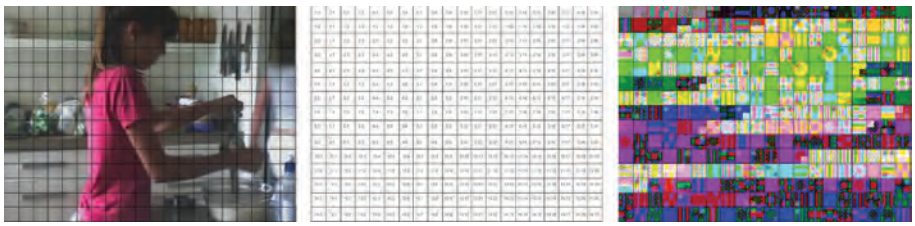


Figure 4. MCU grid (black grid) overlaid by JPEGsnoop on the glitched image.

Using a tool called 'Restart Marker' within JPEGsnoop we can extract specific datasets for each square within the MCU grid. E.g. Equation 1: Position Market @ MCU= [1, 2] (1,1) Block = [3, 5] YCC = [104, 0, 0] Position marker data is employed as numerical datasets specific to each separate MCU square while the

MCU grid is employed as a visual ordering system. Using the position marker numerical data unique to each cube, we can start to manipulate the cubes to result in 300 individual one-off interpretations of digitally decayed code.

3.2. CODE TO FORM

Grasshopper3D as a computational spatial generation and design instrument enables us to define a custom code, turning decayed data files into 3D spatial outcomes. The employed design systems and custom codes have an appreciation for unexpected outcomes that the glitch brings about (figure 5).

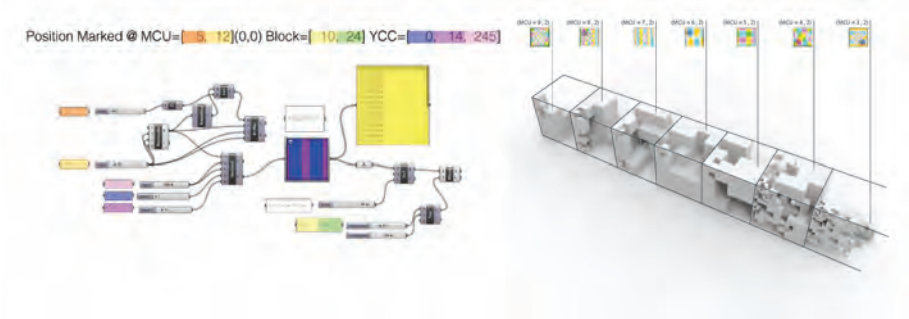


Figure 5. Data from JEPGsnoop into Grasshopper (left); glitch data defining cubes (right).

Glitch is a sudden occurrence of reinterpretation in that moment of time. The architectural outcome at this point stands as a static interpretation of glitch. Cloning (2010) writes that "computer code (like human language) may theoretically exist in a timeless transcendental realm, but in order for it to intersect being, it has to be read by and run on something – a person or a computer. The glitch foregrounds and problematizes this myth of pure transcendental data, of pure and perfect signal. The glitch is a perpetual reminder of the immanent, real-time embodiment of executed code."

3.3. DATAMOSHING MOMENTS IN TIME

Datamoshed stereoscopic 3D animation is resultantly introduced as a means of understanding how glitches work in movement in time within the digital realm. Stereoscopy works by presenting two offset images to the left and right eye, the brain then combines these views to create a perception of depth illusion. This works in a similar way to digital decays shifting of perception in the way a glitch 'tricks' the computer by reinterpreting the visual perception of binary code (figure 6, left). 'Datamoshing' is the process of removing the key frames from a compressed video 'DataStream', causing the motion-vector data to not understand where the first clip ends and the next clip begins resulting in a merging of clips in a distorted and glitched way (figure 6, right).

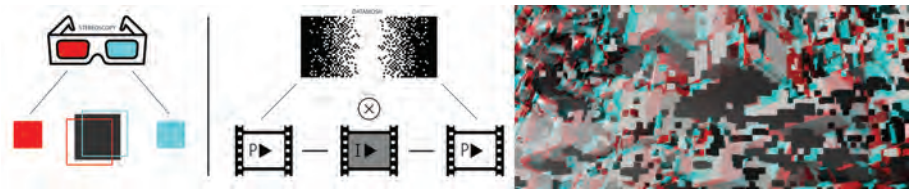


Figure 6. Stereoscopic process for anaglyph visualisation (left). Datamoshing process diagram (middle). Animation result (right).

This project deploys stereoscopic techniques and animation which are not the focal point but merely a tool to enhance the datamoshing employed to express an idea and deepen an understanding of glitches happening in digital time and space (figure 6).

Through datamoshing in stereoscopic 3D, it begins to be legible that glitch can be performed in three dimensional space and how it effects the digital dimensional space. David OReilly, who created the Adventure time episode 'A glitch is a glitch', states that working in 3D digitally is constant communication between software and idea while "it's weird NOT to acknowledge that everything is fake and animation is basically an optical illusion ... it's just something that happens in the translation process from brain to screen" (Rourke 2013).

3.4. DIGITAL STEREOSCOPIC GLITCH SPACES

Stereoscopy techniques employed in the previous experiment work by having a left and right offset of the original form, left being red and right being cyan. Red and cyan are chromatic opposites allowing the brain to merge the two offset of opposing colours into one neutral form (Figure 6). Here we question how stereoscopic colours and methods can be employed into digital architectural form to obscure our interpretations in the same way a glitch obscures the computers interpretations of digital code.

Blender as an open source 3D modelling program has the ability to export a specific output format resulting in a modestly unsophisticated codec using just vertices and faces. Digital 3D files are commonly incredibly inflexible in terms of code manipulation due to exceptionally constricting codec systems. Exploiting this discovery, we employ a code simplification process by separating each unique MCU cube created in Grasshopper into separate *Rhinoceros3D* files. We now have all 300 cubes in separate files that we put through the code simplification process of importing and exporting OBJ through Blender resulting in 300 unique OBJ file digital 3D forms. Next each individual file is manipulated through hex code find and replace systems based on their 'X' and 'Y' co-ordinates in the original MCU grid layout in a program called Hexfiend, once for red where 'Y' is replaced with 'X' co-ordinate in the binary code: e.g. every '7' replaced with '4', and again the cyan manipulation where 'X' is replaced with 'Y' e.g. every '14' replaced with '7' (figure 7). This creates a unique left and right offset per cube in the same way stereoscopic offset works, though the offsets are being determined by the cubes position in the original MCU grid plan instead of the conventional inter-axial separation of '6.5'.



Figure 7. Workflow graphic showing an array of tools used to glitch the actual 3D form using their X and Y co-ordinates in the MCU grid and employing chromatically opposite colours from stereoscopic methods to further glitch digital architectural form.

An appreciation for unexpected outcome returns when manipulating the bones of the form through code variations as shifting numerical data is a blind process until the form is reopened. This laborious process results in three unique shifted perceptions for each individual form in the MCU grid of 300. We combine each set to create an unimaginable architectural interpretation of digital decay processes. When the forms are viewed with the anaglyph red and cyan glasses on the perception of space and depth is distorted creating a chaotic interpretation (figure 8)

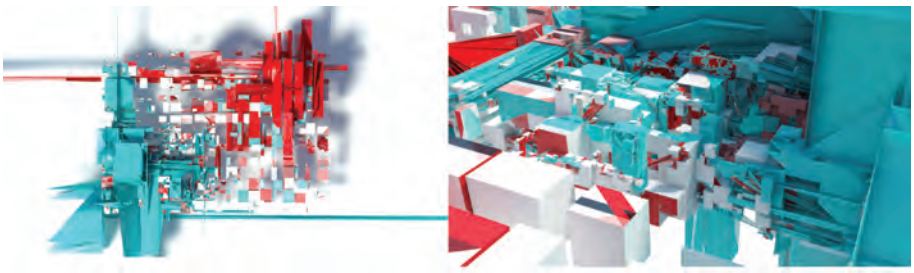


Figure 8. Anaglyph digital architecture (to be viewed using anaglyph glasses).

3.5. DIGITAL MATERIALITY

Texture-based material components are 'habitually' applied onto digital architecture models aiding human ability to connect digital form to physical environment. Arguably this helps comprehend forms' buildability and link virtual geometric entities to a relatable scale. Three preeminent material types that are conventional to architectural visualisation have been arbitrarily selected; concrete, metal and glass (figure 9).

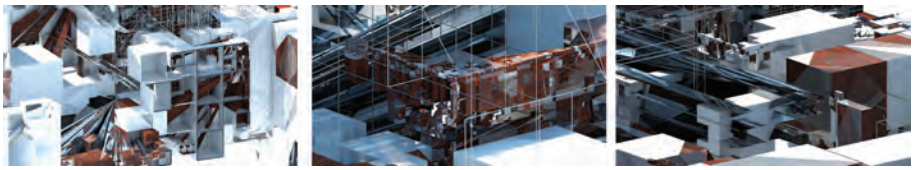


Figure 9. Conventional architectural material application.

We found that textured forms have somewhat similar effects to that of natural glitches activated throughout the datamoshed animation in the way we experience tension and release in clarity and confusion. Where there is glass, we perceive a window; where there is metal, we imagine a rusty street alleyway; the piping looks to be a jungle gym or climbing ladder of sorts and the concrete is perhaps a large apartment complex. Where forms relatability to our known physical environments is ambiguous, our perception is blurred. In these moments of confusion, the brain almost skips and jumps along the forms to the applicable moments of clarity. It is this tension and release of confusion and clarity throughout the chaotic digital environment that enhances the communication of the behaviour of a glitch through 3D space.

4. Glitch as 'the Given' and as 'the In-Formed'

At the beginning of our experiments, we observed that the encountered glitched photos are rich in 'information aesthetics' that precipitates a decline in 'information perspicuity'. This causal relationship between aesthetics and meaning is not the focus of this research, but the becoming of glitch as 'the in-formed' that meanwhile escapes from an algorithmic protocol of numerical data as 'the given'. The acceptance of glitch that requires the 'prioritisation' of the aesthetic in excess of the algorithmic is prevalent. The comfort zone of such aesthetic understanding exacerbates the first problem by veiling it behind the glitched "candy-coloured" visual outcomes.

In his essay "Are Some Things Unrepresentable?" Galloway (2011) distinguishes data as 'the given' and information as 'the in-formed' by employing the metaphor of falling autumn leaves. Since falling leaves are randomly scattered, they have no information unless somebody forms them, for instance, to spell out a word. Then the leaves gain information which is a word originating from Latin as 'put-into-form', whereas data literally means 'the things having been given', i.e. 'the givens'.

In JPEGsnoop, glitch was initially treated as 'the given' which was actually sitting on a grid in relation to the pixel distribution of the 2D image, i.e. 'the given' was simultaneously 'the in-formed'. The symbiotic relationship between the two forms of glitch was then broken down into further individual pixel units. This exercise led us into 3D conversions of autonomous units where a second problem emerged.

Stereoscopic experiments allowed us not only to explore the notion of 'glitch-space' in 3D but also remap it, yet, without orientation. Further research is planned to continue with glitch in immersive virtual environments technologies in order to provide more insight onto these issues. However, we aim to find a new vertical dimension arising from the dual ontology of glitch placed on the same horizon. Transforming from being 'the given' to 'the in-formed', glitch wants a multitude space to exist which is not permitted by the monochromatic channel imposed by the indentured protocols of the algorithm.

The insufficiency of critical approaches bounds glitch to signification under the broad influence of semiology on architecture. Undertaking a challenging at-

tempt to provide an ontology of glitch-itself, our research looks into the autonomy of glitch towards a theory of glitch-space that emerges from its dichotomised ontology between 2D and 3D. However speculative it may sound, our approach does not totally abandon representational aspects of glitch as an immediate expression of the real. Rather, by using available methodologies and tools, it makes state of the art data interpretations that are instrumental to the challenging task of understanding 'glitch-space'.

5. Conclusions

Digital architectural projects that explore digital spaces allow for a freedom of expression that references reality while also designing the unimaginable. The formal outcome of the here presented design process is an interpretation of glitches happening deep within our digital realm and architectural workflows.

Therefore, digital decay expresses what we cannot comprehend, catalysing the reinterpretation of glitch as a means of designing digital architectural space. This is not reality to virtual where we digitally model something that is built in the physical, nor is it virtual to reality where we digital model something that could be built in the physical. This means of designing is just virtual to virtual where we reinterpret the constraints and natural forces impeding our architectural workflows through digital architectural design.

Our research works with numerical data driven design experiments to interpret and understand glitched data and digital decay through architectural form. Today all stages of architectural design are produced through pixel arrays and digital workflows with both the physical building within the built environment and the digital model within the digital realm existing. With both being exposed to constraints and forces impeding architectural production and maintenance we look into how our digital architectural digitally decays.

The research contributes to the glitch research community by advancing glitch from its 2D representational expressions into 3D digital spatial interpretations. The multidimensionality of the underlying data that is visualized through a glitched 2D image on the computer screen is extended via a contemporary spatial architectural representation to match the original data. Computational architectural design methods allow for a responsive and adaptive re-representation employing current technologies and understanding of architecture. The here reached architectural expression of glitch questions the limitations of digital modelling and deepens the appreciation for human agency within digital creative workflows bringing authenticity to digital decay through contemporary interpretation of the glitched data through design.

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Building Information Modelling

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BIM-SUPPORTED VISUAL LANGUAGE TO DEFINE BUILDING DESIGN REGULATIONS

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Abstract. Growing number of Building Information Modeling (BIM) applications have supported the automated assessment of building design and its quality in the early phase of design. For increasing the accuracy and fineness of assessment, rule interpretations require logical base and standardization of analysis process. Therefore, some government-funded research projects have focused on this rule-making process separated from the rule-checking process. Specifically, KBimLogic is a logic rule-based mechanism designed for the building permit related rules in Korea Building Act sentences. As a com-puter-readable definition of a rule, KBimCode has been developed to be executed in actual rule-checking software. The limitation of such code is the visibility to the rule experts who are usually non- or novice programmers. This paper describes much intuitive way of defining and generating KBimCode through KBim Visual Language. User can easily query the building element and method through the immanent connection with KBimLogic database. By using the KBim Visual Language, various types of rules written in design guideline, international standardization, and national acts can be easily interpreted into computer-readable formats such as KBimCode in order to proceed with the automated rule-checking.

Keywords. BIM (Building Information Modeling); Visual Language; Korea Building Act; Automated Design Process; Rule-making.

1. Introduction

Applications of Building Information Modeling (BIM) have affected the process of building permit to be partially automated by running the 3D building model-based rule-checking systems with related regulations. For the valid rule-checking process, an appropriate rule-making process for the computer-readable rules should

be done in logical interpretation without flaws. The conventional rule-making process primarily depends on the specific software and its own file format, therefore main part of the process is based on the closure method using script language-dependent hard coding process. Consequently, the primary steps of translating regulation are accomplished by software manufacturers or programmers. That makes the high threshold for architects or related parties who have little knowledge about programming language to check building related regulations.

The previous studies for the automated rule-checking have more stresses on the execution algorithms compatible with the IFC (Industry Foundation Classes) structure, often using hard-coded rules. However, for dealing with a broad range of rules in AEC-FM (architecture, engineering, construction and facility management) domain, logical interpretation based on syntactic, lexical, and semantic aspects should be ahead of the rule-making process. Therefore, in the checking software, the translated rules have to be logically valid and reflect the user intention as well. Because of the specific software development environment, only software experts could generate and modify the rules with their own definition. As a result, for the computer executable building rule-making process necessarily needs both architects and programmers to prevent the error-prone translating process.

As the reasonable alternative, this paper introduces BIM-supported visual language-KBim Visual Language (KBVL)- for rule-making which can be handled by the people who are usually non- or novice programmers. The logic rule-based mechanism called KBimLogic and its output KBimCode (Lee et al. 2016) are the basis of a logical structure for the KBVL. Also, KBVL utilizes the meta-databases established as a part of KBimLogic project, including the exact vocabulary of building elements and methods derived from the Korea Building Act.

2. Visual Language for Building Rule-making

Visual language emerged as an object-oriented programming language for developing a delicate algorithm and modifying the result in a parametric way. This also expresses the information as graphical symbols to be easily understood and used by users (Costagliola et al. 2002). Each graphical symbols have both semantic and syntactic attributes and are composed according to the structure definition of language. By the graphical representation, visual language is easy to learn, intuitive to use, and unnecessary for professional knowledge about programming. Consequently, the visual language supports managing information with visual elements and generating parametric logical rules with a complex structure in an intuitive way. In this regard, the visual proceeding makes possible to overcome the limitation of script-language-based hard coding method to reflect complicate relation between building regulations.

Thanks to the high usability of visual language, composing or checking complex contents with intricate relation became approachable. Since the building related regulations are involved with complicated relations between each building elements and include complex provisions, the visual representation is effective to grasp the contents of regulations.

There have been related projects about developing visual language-based build-

ing design regulations. VBQL (Visual Bim Query Language) is for information extraction with filter query especially for craftsmen (Wülfing et al. 2014). As the result of eWorkBau project in Germany, this language could extract specific information from the 5D BIM model. Also, as a similar language, QL4BIM (Query Language for BIM) was developed to simplify the process of 4D BIM analysis. It supports even non-expert about programming to compose node combination to define queries as an intuitive way (Daum et al. 2015). As an expansion of the scope of querying information, language for rule-making and checking such as VCCL (Visual Code Checking Language) was developed for representing the result of building code checking with visual elements (Preidela et al. 2015-2016).

Preceded studies have been mostly focused on querying and checking the simple geometric specification of the building elements. The KBVL differentiates its features by utilizing the database of KBimLogic based on the Korea Building Act. Every element is prescribed in the database by the definition in the Korea Building Act. The semantic querying of visual elements from database decreases the feasibility of logical redundancy or omission between each node among the rule-making process. By standardized definition, user defined rule or any different kind of regulations can be composed of refined contents.

3. Logical Background for KBim Visual Language

This section describes the logical background for KBVL. As shown in figure 1, KBimCode ruleset file deduced as the result of composing components from KBimLogic-meta database. KBVL which for fasten the composition process of KBimCode, visually defines the relation of components by the connections and nodes. Each visual symbol uses the logic structure that already defined as KBimLogic and the definition of components defined in the meta database.

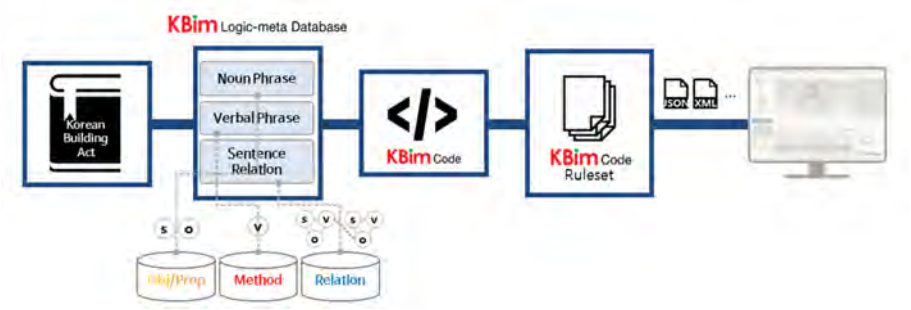


Figure 1. Overview of KBimLogic-translating Korea Building Act into KBimCode.

3.1. GENERATE KBIMCODE BASED ON KBIMLOGIC

To decrease logical error among the user defined KBVL, it puts its basis on the KBimLogic, the logic rule-based mechanism for translating building permit related Korea Building Act into the form of computer-executable format called KBimCode. By the KBimLogic, the rule sentences are split into the irreducible unit to increase accuracy and precision of representing the logical relation between

regulations. As the result, about 2,200 articles of building permit related regulation in Korea Building Act are decomposed into about 15,300 sentences and collected in the database for querying by the relation of other sentences. From the sentences (1) building elements and (2) their properties, (3) logical methods from verb phrase of sentences, and (4) relations between each sentence are extracted and collected as a database called KBimLogic meta-database.

This logic-rule based mechanism and the meta-database are the basis for the structure of BIM-supportive KBimCode by the object mapping with IFC model. The KBimCodes are composed of others according to the relation -commission, and reference- described in the Korea Building Act. As the result of composing, the ruleset file that including complex regulation definition and their relation is generated as computer executable format.

3.2. KBIMLOGIC FOR KBVL

Different with KBimCode which is basically translating Korea Building Acts, KBVL covers various types of regulations that defined by the user. For expanding KBimLogic to the KBVL, KBim meta-database offers standardized library for compounding visual language combination. The objects and properties with specific action that logically predefined in the KBimLogic meta-database are used as a visual element of the KBVL. Since the database is composed of analyzed and gathered components from the Korea Building Act, utilizing database could minimize the fallacy of definition in each visual symbol and increase the reliability of KBVL composition.

KBVL is generated by representing the combination of visual elements by queried attributes from KBimLogic meta-database, and automatically descript KBimCode at the background. By the KBVL, the user easily generates the complicated KBimCode by simplified visual symbols. Automatically generated KBimCode can be exported as the ruleset file to be used in the other rule-checking software.

4. KBim Visual Language

KBVL supports users to understand and implement the building permit related rule-making process without expert knowledge about script-language-based coding system. By the arrangement of visual symbols that already defined and originated in the KBimLogic meta-database, the user can easily compose standardized KBimCode.

4.1. BASIC COMPONENTS OF THE KBIM VISUAL LANGUAGE

The basic components mean two main component - node and connection. The nodes mainly include and symbolize specific information or function to define the action of the data. The connections of nodes automatically generate KBimCode in compliance with its grammar.

4.1.1. Node component

Node is a basic element of the visual language in order to reveal semantic information as well as to exact elements of the building model. As shown in figure 2, the general KBVL node has two kinds of port to import or export the data, title, and content of the node. Based on the distinctive function and feature of each node, this part describes four types of nodes. Each line of content reveals or requires the specific types of information. If the appropriate type of input is entered, color of the input port become black as verifying the connection between nodes, but white color means that nothing is entered and generated through the port.

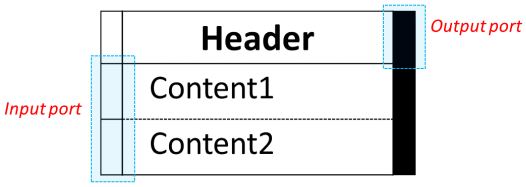
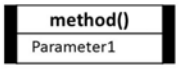
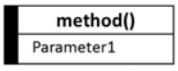
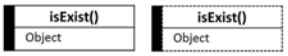
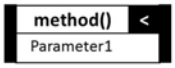
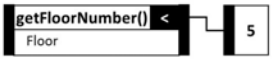


Figure 2. The visual attributes of the general node.

- **Method node:** Method node plays a role of defining an exact action on the inputted object by connection with KBimLogic meta-database. By the linkage with the database, each method has a different action, type and the number of parameters. Based on its classification according to the attributes, basic rule module requires several object nodes to be connected to the input port of the method node, and additional return value node. Table 1 shows appearance features and using examples according to the different return value of the method. Inputted object is treated with the action of the method and the result is described on the method node or additional node. The difference between the method with Boolean return value and the others is whether it requires the return value node. The method with Boolean return value reveals itself the negation as dotted edge line. The other nodes such as the method of collection or numeric value need an additional node which appoints the target value.
- **Object and property node:** As input values for the method node, object and property have to be entered through the input port according to the different types of parameters of the method. Since this node has only the function of querying specific building elements, there is only an output port to be connected with the method node. The another characteristic of the object and property node is that there are several properties which are subordinated with the object and represented as a dotted line in the node content's line by line. Exact querying and mapping occur between the building elements based on the KBimLogic meta-database.
- **Return value node:** As mentioned in the method node section, there are several types of method nodes which are needed to return a value node. The return value node has two types of data type - string and numeric representation. To assign specific collection or numeric value, the return value node is connected to the output port of the method node. The result of method node requires having the value of return value node.

- **Logic node:** Rule-making process has a logical structure based on the CS-KS relation between each rule module. Definition of precise link relation decreases reiteration and unnecessary phase which may cause complicated structure of visual language and delay of the rule-making process. The logic node defines the Condition-Result-Else relation between the rule modules through the output port of the node. The node includes user setting option of adding or deleting the number of input or output port. In the part of 'Condition' section, CS (Condition Statement) is entered as a requirement of checking. 'Result' section includes KS (Key Statement) if the result of conditional checking is true. If the result is false, the result statement is described in the 'Else' section.

Table 1. Appearance feature and explanation of visual element based on different type of return value and using an example.

Feature	Return Value		Using Example
	Feature	**String**: Methods querying the name of collection.	
	Example	getBuildingUsage(), getObjectMaterial(), …	
	Feature	**Boolean**: Methods distinguishing result between true and false.	
	Example	isExist(), isObjectProperty(), …	
	Feature	**Numeric**: Methods querying numeric value (number, count, height …).	
	Example	getObjectCount(), getFloorNumber(), …	

4.1.2. Connection component

The connections of the nodes basically represent the flow of information and complete the node combination of rule modules with complex reference. The connection has two types of representation- solid line and dotted line. The solid line represents the flow of data and connection to the other node through the input port. The other type, dotted line shows 'OR' relation between several nodes. Each independent node combination implies 'AND' relation.

4.2. BASIC RULE MODULE

To generate a basic rule module, at least one combination of the method node with proper object and the return value node are necessary. To evaluated specific and delicate element, CS-KS linkage has to be refined to remove ambiguity involved in contents. The process of fragmentizing the contents of rule as basic rule modules and composing them again as bigger rule module supports making detailed relational indexes which could have been missed. The structure of basic rule module is based on the ALU (Arithmetic Logic Unit) for logical execution. Each basic rule module is composed of a single method node, its object, and property node, return value node according to the type of method, and the connection between each node.

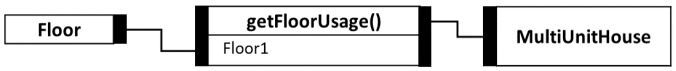


Figure 3. An example of basic rule module for checking whether the floor usage is "MultiUnitHouse".

4.3. NESTING COMPONENT

The nesting relation starts with the basic rule module which is the fundamental level of checking implementation. Each rule module is bound in a box-shaped container as another checking module. To evaluate complicated and delicate elements, several single basic rule modules are connected with other modules. Single node connection also can generate logical rule but through the nested component, repetitive usage of the same node is decreased and detailed checking indexes that could have been missed can be handled without omission. If contents in the checking process include multiple aspects with negation and logical connections, nesting relation can effectively offer intuitive visualization of rule module and connection relation. For example, "myWindow" component is nested with a basic rule module which means the window of which the panel operation type is a swinging window (figure 4).

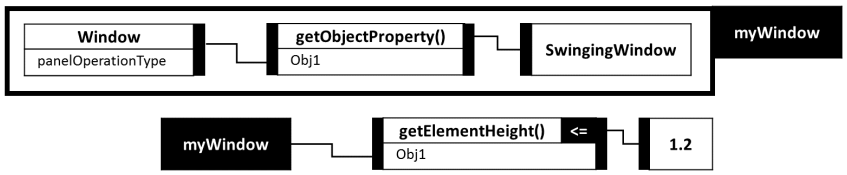


Figure 4. Nesting component in the box for generating specific "myWindow" component.

5. Pilot Test

The pilot test is for verifying the possibility of translating various type of regulations by the KBVL. In this section, the part of Enforcement Decree of the Building Act 35-1 (EDBA 35-1) is represented with KBVL. The original text of EDBA 35-1 is:

- **Enforcement Decree of the Building Act 35-1 (EDBA 35-1):** (Installation of Fire Escape Stairs) Direct stairs installed on the fifth or upper floor or the second or lower underground floor under Article 49 (1) of the Act shall be installed as fire escape stairs or special escape stairs according to the stand-ards prescribed by Ordinance of the Ministry of Land, Infrastructure and Transport.

As in figure 5, for the compact node combination, the specific user-defined object should be predefined by using bound box component. Composed components are used in the overall node combination to maintain and reveal the specific condition of the user defined object. Figure 6 shows CS-KS classification of EDBA 35-1

contents to verify the logical relation between them. Through binding components, each CS and KS nested as single basic rule module and connected with logic node shown in figure 7.

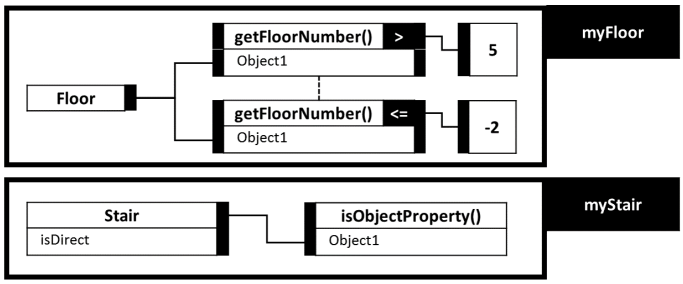


Figure 5. Definition of the specific component "myFloor", and "myStair".

[CS3]*Direct stairs installed on the fifth or upper floor or the second or lower underground floor* under Article 49 (1) of the Act shall be **[KS5]***installed as fire escape stairs or special escape stairs* **[KS4]***according to the standards prescribed by Ordinance of the Ministry of Land, Infrastructure and Transport: Provided*, That the same shall not apply to cases where **[CS1]***main structural parts are made of a fireproof structure or noncombustible materials* and **[CS2]***falls under any of the following subparagraphs*.

Figure 6. CS-KS classification of EDBA 35-1 contents.

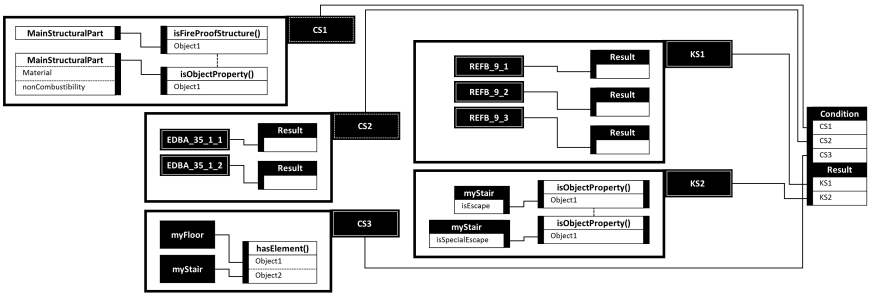


Figure 7. KBVL of EDBA 35-1.

As the result of combining KBVL, the final logic node generates the KBimCode to be extracted as the ruleset file for the execution of the other rule-checking software.

Table 2. Generated KBimCode at the background of KBVL (EDBA 35-1).

Check(EDBA_35_1)

```
IF (!CS1 AND !CS2 AND CS3) THEN (KS1 AND KS2)

CS1 {
     isFireProofStructure(MainStructuralPart) = TRUE
     OR isObjectProperty(MainStructuralPart.Material.nonCombustibility) = TRUE
}

CS2 {
     getResult(EDBA_35_1_1) = TRUE
     OR getResult(EDBA_35_1_2) = TRUE
}

CS3{
          Floor myFloor {
                              >Floor.number > 5
                    OR Floor.number <= -2
          }
          Stair myStair {
                    isObjectProperty(Stair.isDirect) = TRUE
          }
          hasElement(myFloor, myStair) = TRUE
}

KS1 {
          getResult(REFB_9_1) = TRUE
          getResult(REFB_9_2) = TRUE
          getResult(REFB_9_3) = TRUE
}

KS2 {
          isObjectProperty(myStair.isEscape) = TRUE
          OR isObjectProperty(myStair.isSpecialEscape) = TRUE
}
```

6. Conclusion

This paper describes a logical basis and structure element of BIM-supported visual language-KBVL to define the part of building design regulations. To verify the availability of the KBVL, the pilot test proceeded for representing actual rules into the KBVL. As the logical base, KBVL based on the KBimLogic, the logic rule-based mechanism to convert Korea Building Act into the form of computer executable format. As the structure elements, each node expresses the queried semantic attributes from the KBimLogic meta-database. Through the management of the database, KBVL composition also can be managed with standardized contents. The connection of each method node with the required object and return value node generates basic rule module for executing fundamental rule-checking. By composing and nesting several basic rule module, complicate rule can be represented with intuitive visual elements. The conventional rule-making process that based on scripting hard coding is now easily accessible with the composing of the visual element. This research also expanding its application range to not only for the Korea Building Act but also other kinds of regulations such as design guideline and international standard document to cover various type of building design related regulation.

Acknowledgements

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COLLABORATIVE ALGORITHMIC-BASED BUILDING INFORMATION MODELLING

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Abstract. Algorithmic-based Building Information Modelling (A-BIM) allows the development of BIM models through algorithms. In a collaborative environment, A-BIM requires management strategies to deal with concurrent development of architectural projects. However, despite there being several tools that support this type of collaborative work, they are not appropriate for A-BIM because: (1) they track changes in the generated model instead of the code where the changes originate from, and (2) they are vendor-specific while A-BIM models might be generated for different BIM applications. In this paper, we discuss the use of Version Control (VC) for project management and concurrent development of A-BIM projects. We evaluate VC for A-BIM through a series of scenarios in the context of a case study.

Keywords. Algorithmic Design; Programming; Algorithmic-based Building Information Modelling; Version Control; Collaborative Design.

1. Introduction

Over the years, the merits of Algorithmic Design (AD) have been extensively researched in the Architecture, Engineering and Construction industries, from the integrated design and fabrication of complex freeform geometries (Kolarevic 2003; Pottmann et al. 2015) to the automation of repetitive, time-consuming tasks and processes (Burry 2011; Santos et al. 2012).

However, despite having been explored with Computer-Aided Design, AD has only recently started to be addressed in the context of Building Information Modelling (BIM). With BIM, an integrated database of building information is developed collaboratively amongst the different members of the project team in order to digitally simulate the planning, design, construction and operation of a building (Azhar et al. 2009; Eastman et al. 2008).

In the past, an approach named *Algorithmic-based Building Information Modelling* (A-BIM) was proposed, which combines AD with BIM (Feist et al. 2016). A-BIM is the use of algorithms to generate BIM models, which are indistinguishable from manually generated ones. However, instead of having the user providing the building information directly to the BIM model, in A-BIM this information is provided by the algorithm that produces the model, using primitive operations that create building components. This approach can also be used to generate identical models in different BIM applications, thus reducing interoperability issues which cripple collaborative practices.

Like traditional BIM, A-BIM also benefits from collaborative development processes. However, A-BIM requires different management strategies to handle the inputs produced by the multiple participants. Issues such as the concurrent development of programs, the coordination between individuals, and management of information, are important challenges that must be taken into account.

When using CAD and BIM applications in the traditional manual way, development teams can use tools, such as Autodesk's Vault and Bentley's ProjectBank, to facilitate collaborative work, allowing team members to develop the model in parallel and track changes made by other team members. However, these tools are not appropriate for algorithmic approaches such as A-BIM, since changes need to be tracked in the code, instead of the model, and models might be generated in multiple tools.

Version control (VC) systems (Brindescu et al. 2014) can offer a solution to these limitations. These systems have been used in Computer Science for many years, which has led to the development of several tools, such as Concurrent Versions System (CVS) and Git. Due to the algorithmic nature of A-BIM, these tools might be more appropriate than the ones traditionally used with CAD and BIM applications, making differences in code easier to detect and manage. In this paper, we explain VC and discuss its potential to manage the development of collaborative AD projects, specifically in the case of A-BIM. Afterwards, we discuss and analyse the application of VC through a series of scenarios found in the development of a collaborative case study.

2. Version Control

Collaboration in software development is supported by a variety of tools, among which VC systems. VC helps programmers control and manage changes introduced by multiple developers. By storing every change made by every programmer involved, VC preserves the project's history and allows individual changes to be identified, along with their author, date and purpose. This enables developers to go back to earlier versions of the project to check, modify, or revert changes introduced earlier.

VC also supports independent, concurrent work through *Branching* and *Merging*. Branching is used to pursue independent lines of development in the project, e.g. a new feature for the program. By isolating different lines of development in separate branches, developers can work independently on separate changes without affecting others, until they are ready to share those changes with the main line

of development. Branching also ensures that unstable code is never introduced into the main line. Once independent changes are ready to be integrated, developers can merge their branches back into the main line (figure 1). Merging combines changes from multiples branches into a single one. If changes are compatible, e.g., if two completely different parts of the program were modified, then they can be automatically merged. On the other hand, if changes are incompatible, the developers are informed about the conflict and have to manually solve it. Conflict detection in VC systems is based in the textual comparison of different versions, which means that these systems are more appropriate for textual programming languages.

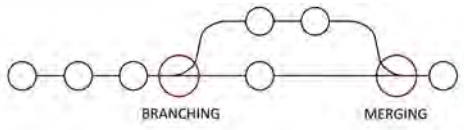


Figure 1. Merging process between two branches. Black circles represent recorded instances in the development of the project where changes were introduced.

VC systems can be either centralized or distributed (figure 2). While Centralized Version Control (CVC) stores the project's information in a single central repository, with Distributed Version Control (DVC) each developer gets their own local repository with all of the project's information. With CVC, in order to make changes to a file located in the central repository, a developer can get a working copy of the original file, which can then be modified and used to create a new version of the original file in the repository. While a developer is making changes to a file, CVC systems rely on a file locking mechanism that prevents other developers from making changes to that file until it is no longer being modified. This mechanism ensures that no one starts to work on a file which may soon become outdated. At the same time, while locked, the file cannot be modified by other designers, even if they intend to modify different parts of the program. In other words, file locking assumes that changes made to the same file by different developers will be incompatible, which may or may not be the case.

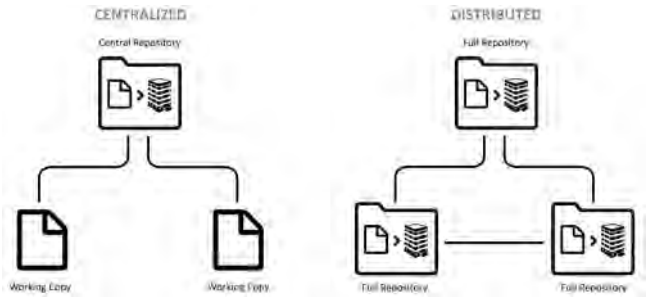


Figure 2. Centralized Version Control vs. Distributed Version Control.

On the other hand, DVC systems allow developers to work locally and independently in their own local repositories until they are ready to share their changes with other developers. This provides a safer environment for developers to experiment with the project without having to worry about the repository's integrity. Once a developer completes a set of changes, they can check the progress of the project to see if any other changes have been made before sharing their own changes with other developers. If so, unless changes are incompatible, they can be merged with other repositories with ease.

While software developers generally find CVC systems easier to learn and use, they usually prefer DVC systems due to (1) the ability to share the work only when it is complete and (2) a better record and management of software changes. Despite the steeper learning curve, DVC systems can offer higher productivity than CVC systems (Brindescu et al. 2014).

3. Versioning and Management Tools

Designing a building often involves a necessarily complex process. It requires collaboration among a large number of participants with different specialized skills, priorities, and objectives (Rosenman et al. 2007). Despite working towards a common goal, these participants typically work independently on different parts of the problem, each using the methods and tools that best fit their needs (Kvan 2000). This might lead to several individuals working concurrently with the same information and set of files, which can be a challenge. To mitigate this, tools have been developed to manage the different inputs produced by the multiple participants.

One of these systems is Autodesk's Vault, a management tool that tracks changes in the submitted files and maintains VC over these. Vault also supports collaborative development, since it allows several users to access and manipulate these files, which can also be locked, preventing changes from being made by several members at the same time. With Vault, users can also see the files' history, reverting them to previous versions if needed, or recovering deleted files.

Another system is ProjectBank, a collaborative engineering data repository by Bentley Systems. This system has similar revision capabilities as Vault but adopts an optimistic approach regarding access to the data in the repository, allowing more than one user to access the same data simultaneously. This strategy is used in order to improve parallel development, by assuming that there is a certain degree of coordination between team members to avoid conflicting changes. When a user is modifying a file, it is only possible to submit those changes if they are the only differences between the user's copy of the file and the server version. If there are other differences, this might lead to conflicts. To handle this issue, ProjectBank allows users to implement a *changeMerge* method to detect conflicting changes, which have to be solved with human intervention (Aish 2000).

While these tools facilitate collaborative work in design projects, they are tailored to deal with files generated by CAD or BIM tools and are not appropriate for algorithmic approaches, such as A-BIM, where the model is generated by an algorithm and a single change to this algorithm or to its inputs might generate a completely different model, making it very difficult to track the changes in it. To

solve this problem, the changes need to be tracked in the code itself. This means that VC has to be done in the code files instead of the model files that are repeatedly generated upon the execution of the code.

Code-related VC is well known in software development and there are already several tools that accomplish this task. In this paper, we claim that these tools are more appropriate to support design projects developed using algorithmic approaches and, in fact, some are already being used in architectural studios. One example is Subversion, a CVC system used by Gehry Tehnologies to support shared repositories for internationally distributed projects, such as the Foundation Louis Vuitton in Paris (Burry & Holzer 2005).

More recently, a DVC system became very popular: Git (Chacon & Straub 2014). Git encourages Branching and Merging to implement changes, allowing users to easily switch between different development branches, and making it easy to test solutions in different versions of the code. Git repositories are hosted by several services, such as GitHub, allowing for a wider collaboration, meaning that collaborators can download, test, review, and further develop the code. With the use of GitHub, several community projects have been developed for many areas, including architecture, e.g. DynamoDS [1] and Lyrebird [2].

4. Version Control for A-BIM

Despite the usefulness of CVC systems for small-scale projects, we consider that larger-scale A-BIM projects are better served by DVC systems since, when working collaboratively, design teams usually work independently on their own parts of the design of the building. DVC systems support this workflow by allowing developers to work locally and independently and only share their work when they are ready to do so. On the other hand, using CVC systems, submitted changes are immediately shared with other team members, regardless of whether the authors are ready to share them, or other developers are ready to accept them. Moreover, CVC systems have inflexible protocols (e.g., the file locking mechanism) and hierarchical structures, which can prove to be an obstacle for creative flexibility and concurrent development during early design stages (Burry & Holzer 2005).

In order to show how VC can be applied to A-BIM, the following sections describe a set of scenarios where it greatly benefits the development of architectural projects. We chose the Absolute World Towers, designed by MAD Architects, as a case study, which we modelled using an A-BIM approach with the Rosetta programming environment (Feist et al. 2016), using the Racket programming language. The model was generated in both Revit and ArchiCAD, the BIM applications supported by Rosetta. VC was supported by Git using the GitHub desktop client.

To start the project, a repository was created by one of the developers. The other developers cloned the repository, in order to have their own copy that could be developed independently from the original one. Every time a developer made changes to the project, they were recorded in the repository of that developer and were eventually shared with the others.

4.1. PURSUING DEVELOPMENT OPPORTUNITIES

When developing a design project, there might be several different ways to accomplish the same goals. For an approach like A-BIM, where the model is generated by algorithms, this might lead to the definition of different algorithms to test which one is preferable. Without a VC System, the designer either keeps different versions of the algorithm in the same file, of which only one is active at a time, or he uses different files, each with one version, managing the dependencies between files so that only one is actually being used. Either way, this is a cumbersome and error-prone task that might lead to bugs and loss of information.

Regarding the Absolute Towers' program, we initially wanted the code to be highly parameterized when modelling the elevators. We wanted the dimensions of the elevators and of the corresponding shaft to be parametrically calculated in relation to the available space, as well as in accordance with a set of regulations defined in the form of parametric constraints. However, we were not entirely sure that this approach would be feasible and so, to develop this idea, we created a branch to avoid disturbing the main line of development, with the expectation of later merging it with the main branch. In the end, this line of development was abandoned due to lack of time as well as limited payoff, since the development effort was too large for the time-frame available for the project. Nevertheless, if needed, Git still allows us to recover the abandoned branch to continue its development in the future.

4.2. FACILITATING CONCURRENT DEVELOPMENT

The previous scenario addressed a situation where there was only one designer developing the program. However, in a collaborative project, the program is developed by a team, and in order to have more control over the evolution of the project, it is important to keep track of the change history as well as each designer's contribution. Furthermore, when working concurrently, each designer is given their own copy of the project files that can be developed and tested independently from the others. When a task is complete, a designer notifies the others and they can incorporate the changes as they see fit.

Without VC, all changes have to be manually identified and merged, and are not recorded for future reference. Moreover, if some modifications are not identified, they can be overlooked when combining the code. On the other hand, DVC systems explicitly support this type of development scenario, making it easier to manage.

During the development of our case study, we divided modelling tasks among two designers. For this scenario, we will consider a task that required, on one hand, the creation of window frames for the tower, and, on the other, the introduction of guardrails on every floor. Using their own repositories, each of the developers worked in the corresponding part of the code. When the window frames were finished, the designer used the GitHub client to record the modifications in his repository. After that, a notification was issued to the other designer, asking him to accept the changes that were made. After this request was accepted, the code for the window frames was automatically merged, which means that it was included

in the other repository. An identical process was done when the guardrails were completed by the other designer, so that both designers had identical and complete versions of the code.

4.3. RESOLVING CONFLICTING CHANGES

When working concurrently on the same project, designers will often work independently on individually assigned tasks, which might result in two designers inadvertently modifying the same part of the program. Most of the times, these modifications can be easily combined to fit both designers needs, but sometimes modifications can be directly contradictory or too different to be combined. When these incompatible changes happen, one or both of the designers will have to find a way to peacefully solve the conflict. Like the former scenario, without VC, these changes have to be manually identified and merged, with the necessary measures to solve the conflict. However, VC systems have features to simplify conflict resolution, namely the identification of the conflicting lines of code.

As an example, during the development of the Absolute Towers, one update to the way slabs work interfered with code regarding the creation of floor levels. This occured because two developers changed the same lines of code for the floor levels differently and at the same time, which resulted in a conflict when trying to merge the changes back into the original repository. When using Git to merge the code, the conflict was identified and the application showed the parts of the code that were incompatible, allowing the user to choose which parts of the code should be kept to do the merge successfully.

5. Evaluation

By analysing the previously presented scenarios, it is possible to compare what designers can do with VC and how they could do the same thing without it. Table 1 shows this comparison for the three presented scenarios.

Table 1. Development of A-BIM projects with and without VC.

Task	Version Control Approach	Traditional Approach
Pursuing Development Opportunities	The designer's repository keeps every version of the code and additional development branches can be created.	The designer keeps different lines of development in separate files or as different fragments of code in the same file.
Concurrent Development	Each designer has a copy of the project that can be developed independently, and then safely merged.	All designers have to keep track of what was modified in order to manually combine changes or risk overwritting files.
Resolving Conflicts	The VC system shows where the conflict occurs and the designers decide which parts of the code should be kept.	The designers have to be able to identify the conflicting parts and manually resolve the conflict.

By analysing the first task in table 1, we note that, if designers wish to store possible lines of development for future projects, with the traditional approach, they have to save their code in different files. If the number of files is small, this is not a problematic task, and can be easily managed without VC. However, in more complex projects, if designers have to produce and maintain several dozen files,

this can quickly become very difficult and error-prone. Furthermore, using this approach, it is common to lose intermediate versions, which naturally disappear as the project evolves. With VC, each version is saved in the repository and it is possible to easily identify changes between versions.

Regarding the concurrent development of A-BIM projects, if two designers want to work simultaneously on the same file, either one waits for the other to finish his changes or they have to work on copies of the file and, afterwards, coordinate with each other to manually identify and combine the changes. On the other hand, with VC systems, users have full copies of the project that can be developed independently. Each time a designer wants to share his work, he requests a merge into the other designer's copy. If there are no conflicts, the changes are merged automatically, sparing a great amount of manual work that is unavoidable when working without VC.

Finally, when conflicts are introduced by designers changing the same files at the same time, VC systems can clearly identify the conflicting lines of code. Sometimes, the conflict cannot be automatically solved by the system without human intervention but, even in those cases, designers have clear information about what was changed and what is in conflict. This is helpful information for resolving the conflict that is not available without the use of VC.

5.1. SUGGESTED WORKFLOW AND LIMITATIONS

Taking into consideration the advantages of VC, we propose a workflow for the use of VC systems in algorithmic-based architectural projects. For this workflow, we recommend DVC systems, such as Git.

Considering the development of a building using an algorithmic approach, the first step would be to create a new repository dedicated to that project. Afterwards, each collaborator of the project must clone the repository containing the project files, in order to have access to it and develop their tasks independently. Each collaborator will have a set of tasks assigned to him, and will create a branch to develop the code for each task. During the development of the tasks, changes will be locally recorded, creating new versions, which allows developers to revert to older versions of the code if necessary. When a task is completed, a request to merge the code is issued by the developer of that task, so that others can, if they want to, incorporate his code in their repositories. If the changes do not cause conflicts, they are automatically merged by the VC system. Otherwise, the VC system identifies the conflicting code, and the conflict must be solved manually by the developers.

Although the proposed workflow is suited for the development of projects using textual programming languages, it has limitations regarding visual programming languages, such as Grasshopper. Since current VC systems are tailored for textual files, they can detect that the visual program was changed but cannot easily identify what was changed. To apply VC to visual programming languages, the system should be able to read the visual program and identify the elements that were added, deleted, or modified. To present those changes, these elements could be highlighted with a color scheme, e.g. green for added elements, red for deleted

ones, and yellow for modified ones. This is a promising line of research that we are considering for future work.

So far, we only discussed the tracking of changes in the code itself. However, it is interesting to be able to visualize those changes in the generated model. This requires *traceability*, i.e., a correlation between models and the code that generates them (Leitão et al. 2014), so that we can identify the changes in the code and trace them back to the model, which is something that VC systems are not capable of doing. We plan to take advantage of traceability to highlight in the model the changes between different versions of the program.

6. Conclusion

The design approaches used in Architecture have been changing throughout the years, becoming more sophisticated as technology evolves. More recently, AD approaches, such as A-BIM, have been adopted to develop more complex projects. Since these approaches rely on algorithms and code files that produce the model, instead of the model itself, the tools that were traditionally used for collaborative work with BIM and CAD applications are no longer appropriate. However, tools used in software development present a good alternative to work with algorithmic approaches.

VC systems allow software developers to, not only maintain versions of their programs, but also create parallel branches to explore alternative software features without interfering with someone else's work. These systems can also track changes and help developers merge their work, making it easier to have several developers working concurrently in the project files.

Due to the algorithmic nature of A-BIM, it is useful to take advantage of VC systems while developing projects with this type of approach. VC helps designers develop new versions of their algorithms, or retrieve old ones if necessary, as well as explore design alternatives in new branches of development.

We showed several scenarios, based on the development of a case study with A-BIM, where VC proved to be helpful to designers by making it easier to deal with several versions of code, parallel development, and even conflict management when two designers modify the same file at the same time.

By comparing what was done with VC with the alternative without these systems, we see that VC greatly reduces the amount of work designers have to do, by automating some tasks and making others easier to perform, such as tracking conflicting changes and helping designers solve them.

It should be noted that these strategies only work with textual programming languages. VC systems are designed to compare textual files in order to accurately detect differences between versions and classify those differences as conflicting or not. Due to their graphical nature, visual programming languages are not easily supported by VC systems, currently making textual programming languages preferable for this type of development.

We conclude that VC systems are useful tools for the development of projects that use algorithmic approaches with textual programming languages. In the future, we will continue to explore VC for collaborative architectural projects as well as

other software development practices that might be appropriate when developing projects with algorithmic approaches.

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GREEN STANDARD FOR ENERGY AND ENVIRONMENTAL DESIGN

The Development of an Assessment System Based on a Green BIM Template

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Abstract. To construct a building that meets the requirements of certification in terms of environmental friendliness, there must be a process that considers the certification criteria from the initial design phase. However, there are numerous complicated task performance procedures to analyse many required items in detail as well as perceive and apply the data requirements efficiently. Currently, Building Information Modeling (BIM) is gaining attention as a solution for environmental problems in architecture. BIM shows precisely how a virtual building is modelled in the real world, thereby providing an objective information and analysis through a simulation. However, the result values of BIM library or modelling may turn out differently as a result of the work environment of designers or users that is not standardized. Therefore, this study applies the modelled and extracted BIM data using the template and library established in the BIM add-in planning and design phase to review in advance the Green Standard for Energy and Environmental Design (G-SEED) assessment by item and manual input of users with the BIM-based (add-in) G-SEED assessment system, thereby providing support to enable users to establish specific strategies in designing green buildings.

Keywords. GBT; G-SEED; BIM System; BIM Add-in; Apartment.

1. Introduction

Buildings have performed a leading role in the global environment, such as energy depletion and environmental pollution; thus, concerns have been raised as regards the need for green buildings in advanced countries where the Convention on Climate Change is adopted.

In Korea, the Korea Institute of Civil Engineering and Building Technology has discussed building energy use and reduction of CO2 emissions actively, with a series of perceptions on the environment; through the discussions, it has strived to find a certification system to reduce environmental load on buildings and improve environmental quality level(KICT 2015).

Since 2002, the Ministries of Environment and Construction and Transportation (currently named the Ministry of Land, Infrastructure and Transport) have implemented the government-led Green Building Certification System. Systems related to green housing that have redundant certification criteria and subject were integrated and unified in February 2013 by the Building Act and Housing Act, resulting in the official launching of the Green Standard for Energy and Environmental Design (G-SEED). This has become the judgment criteria for environmental friendliness of buildings, as designers now produce G-SEED-based environmental designs to design green buildings (Kim 2014).

However, there are numerous complicated task performance procedures for the designer to analyse many required items in detail from the initial design phase as well as perceive and apply the data requirements efficiently.

Thus, to promote G-SEED-based green buildings, it is necessary to develop a new application technique that can provide more efficient support for detailed items of certification.

Building Information Modeling (BIM)-based G-SEED assessment system can be used to cope actively with the above concern. The G-SEED Certification Assessment BIM System (GCS) is a system that provides an environment in which information that can assess the criteria of G-SEED through Green BIM Template (GBT), including environmental quality level data, is extracted within the Autodesk Revit® environment automatically, and the final certification grade can be determined.

Therefore, this study will establish green building data through GBT so that designers can implement prompt and objective green building from the initial design phase, and propose a BIM system that can confirm the green building certification scores and grades in GCS based on the above.

2. Theoretical Discussions

The focus of green buildings is to minimise environmental loads in designing, constructing, and maintaining buildings, and to find ways to maximize social and economic benefits (Kim et al. 2008). There are various concepts of green buildings, but the common idea is that green buildings can only be achieved by understanding and approaching integrated building performance and environmental data. Buildings have different conditions, and thus there is a need for an adequate design technique in line with the balance of all kinds of environmental analysis data based on specialized understanding and knowledge of energy efficiency (Kim 2015).

2.1. KOREAN AND OVERSEAS GREEN BUILDING CERTIFICATION ASSESSMENT PROGRAMS

Table 1 shows the assessment programs developed in Korea and overseas as regard green building certification.

The GBT-based G-SEED assessment system in Korea performs assessment by linking BIM-based data to Microsoft Access and provides the results on Microsoft Excel; such system is inconvenient for users to establish and assess the BIM model compared with that in the United States and Japan. To contribute to the promotion of green building, it is necessary to provide an efficient assessment system for users, such as the BIM authoring tool add-in assessment system similar to the cases overseas.

Table 1. Assessment programs for green building certification in Korea and Overseas.

Division	VE-Toolkit for LEED	Revit Extension for CASBEE	GBT based G-SEED Evaluation System
National	Unite State	Japan	Korea
Organization	USGBC	JSBC	Hanyang Univ.
Years	2009	2010	2014
Feature	- Revit Add-In System (BIM Application) - 10 items among 72 items of evaluation system - Select building type and environmental element	- Revit Add-In System (BIM Application) - 12 items among 92 items of evaluation system - Use a separate evaluation tool	- BIM platform data evaluated in conjunction with Microsoft Access and Microsoft Excel provide results
Image			

2.2. ANALYSIS OF G-SEED'S ASSESSMENT ITEMS

This study applied apartment buildings, which are general buildings and have received the most assessment since the implementation of the green building certification system, as the assessment standard. This study analysed the BIM-based assessment possibility of 41 assessment items, excluding those in remodelling and dwelling performance, out of total 54 items of the G-SEED apartment assessment certification criteria announced in June 2013.

The analysis results showed that there were 17 out of 41 items that can be built with BIM data among design data necessary in the G-SEED assessment items. As shown in table 2, 11 of 17 items that are assessed automatically using BIM data are built with the BIM system. Items, such as 7.3.1 light-weight impact sound insulation and 7.3.2 heavy-weight impact sound insulation, require users to enter the value of floor impact sound pressure level, and thus are excluded from the automatic input method (Kim 2014).

Table 2. Information classification system for G-SEED items.

Assessment List	Classification	Information	Using
1.1.1 Ecological value	shape	area	part
1.2.1 Daylight interference prevention plan	shape	distance	part
1.3.1 Community center and facility plan	shape	area	whole
3.1.1 Floor plan for life-style change	shape	length	whole
3.2.1 Living furniture use prevention plan	shape	area	whole
3.3.1 Separate collection of recyclable material	attribute	separate collection container	whole
3.4.1 Certified green product use for valid resource recycling	attribute	eco-friendly certified product	whole
3.4.2 Carbon emission footprint of material	attribute	material's carbon emission quantity	whole
4.1.1 Rainwater load reduction plan	shape	area	part
4.2.2 Rainwater use	shape	area	part
6.1.1 Connected green axis plan	shape	area	part
6.1.2 Natural soil green area rate	shape	area	whole
6.2.1 Ecological area rate	shape	area	part
7.1.2 Natural ventilation plan	shape	area	whole
7.3.1 Light floor impact sound prevention	attribute	Light weight sound	whole
7.3.2 Heavy floor impact sound prevention	attribute	weight sound	whole
7.3.3 Noise protection between units	shape, attribute	wall thickness	whole

Thus, 9 of total 41 items, composing of 22%, can be assessed with the BIM-based automatic input method. Thirty-two items, excluding nine items of the BIM-based automatic input method, require users to enter the scores manually based on direct assessment criteria.

2.3. BIM-BASED DATA BUILDING METHOD

The BIM model is a 3D modelling technique and a design tool with object information. Thus, it is necessary to build a library that includes an object information. To assess the items of G-SEED, this study established a library of the key elements of a building, such as walls, floors, and windows that include relevant information, as shown in table 3, and conducted BIM modelling using the library to extract the data of the BIM model (Hong and Lee 2013).

To extract information from the BIM model, a list (txt), which is a data extraction method for BIM authoring tool, was used. As shown in table 3, the list is a table of data extracted from the elements of the building modelled with the BIM authoring tool. The data that changed in the process of revising the modelling are updated on the list automatically; this process bears the benefit of being able to extract data by reflecting the changes (Kim 2015).

3. Building Process of G-SEED Certification Assessment BIM System

As regards green building, the government is mandatorily implementing and expanding policies while also promoting adoption of BIM to support them; however, there is still not enough practical and specific system to make assessments. Evaluating and simulating environmental performance requires input of environmental data on building information as well as detailed additional tasks of modelling data. However, there is no system to guide users through the process.

Table 3. BIM based database (library, schedule).

Library Type	Library Attribute		
wall	ID data	measurement	materials
	· annotation · mark · pure resource code	· thickness · area · width · volume	· material
	text	etc	
	· main material structure · structure · structural use	· eco-friendly certified · carbon emission quantity	
floor	ID data	measurement	materials
	· annotation · mark · pure resource code	· thickness · area · slope · volume	· material
	text	etc	
	· main material structure · structure	· eco-friendly certified · carbon emission quantity	
door	composition	measurement	materials
	· shape · function · wall finish · construction type	· thickness · height · frame thickness	· frame materials · glass materials · door materials
	text	etc	
	· main materials · pure resource code	· eco-friendly certified · carbon emission quantity	
window	composition	measurement	materials
	· shape · function · wall finish · construction type	· thickness · height · frame thickness · area · width · height	· frame materials · glass materials · door materials
	text	etc	
	· main materials · pure resource code	· eco-friendly certified · carbon emission quantity	

Schedule (unit : m^2)

<GBS_3.2.1 Validity of plan for inhibiting use of household furniture - room>

A	B
kind of room	area
balcony	33
bathroom	27
dress room	12
entrance	16
kitchen	56
living room	121
room	150
room,closet	6

In this perspective, this study suggests that G-SEED certification assessment BIM system could serve as a system that can guide modelling using the BIM-based template GBT and manage the scores and grades constantly to obtain green building certification.

GBT is a method that interworks BIM data with G-SEED detailed items, and provides an environment to judge the environmental performance objectively. This increases convenience in building data according to the purposes of users by guiding the modelling, and also enables efficient data management.

GCS, which implements G-SEED certification assessment in the same environment based on the modelling that used GBT, is an environment that can show the results of the output data for the input data. By using this system, users will receive results according to the G-SEED certification items. This performs the role of helping users understand and implement integrated environmental data on green building.

3.1. G-SEED CERTIFICATION ASSESSMENT BIM SYSTEM SCENARIO

The G-SEED Certification Assessment BIM System using GBT consists of the data phase and BIM modelling phase of GBT(i), and BIM add-in implementation, evaluation and result phase of GBT(o), as shown in figure 1 (Jun et al. 2015).

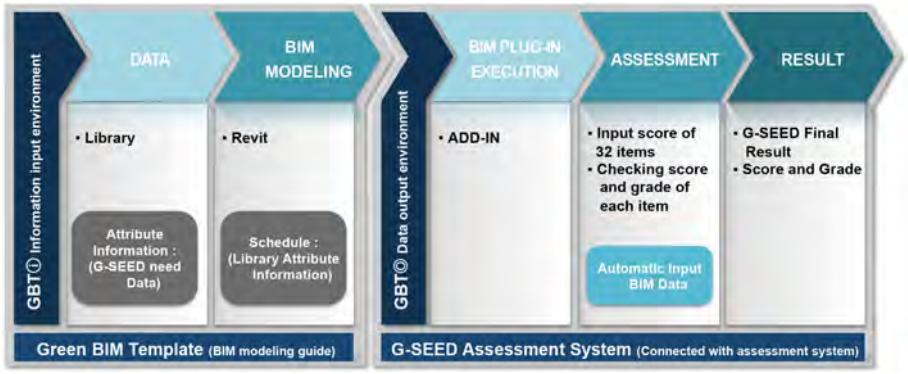


Figure 1. Scenario of GCS.

In the data phase, attribute data is set in the library provided for users to extract necessary data for evaluation, as the G-SEED evaluation criteria. In the BIM modelling phase, modelling is performed with the library, including attribute data, whereas modelling data, according to the attribute data on the list established to enable automatic input of data for evaluation, are extracted in the GBT(o) environment. The BIM add-in implementation, evaluation, and result phases conduct evaluation with the BIM authoring tool add-in system and provide the final results to users.

3.2. BIM ADD-IN DEVELOPMENTMENT PROCESS

This system was built in the form of Revit 2015 add-in using SDK basically provided by the BIM authoring tool Revit with the C# development language in Visual Studio 2015 developed by Microsoft.

The development process in figure 2 shows that Revit SDK is used in the C# project to create the C# source file, with reference to the DB according to UI and attribute data, thus coming up with nine items of automatic input and codes for the manual input and final results. The DB of the BIM authoring tool is DB of the BIM model according to the attribute data necessary for evaluating each item, and the logic according to the evaluation criteria for each item is coded, providing

the final results of total scores and grades for users through automatic input of nine items and manual input of 32 items. The proposed BIM add-in is an add-in system designed by users based on BIM and that can be applied immediately, thereby customized for users to perform G-SEED evaluation in a BIM authoring tool environment.

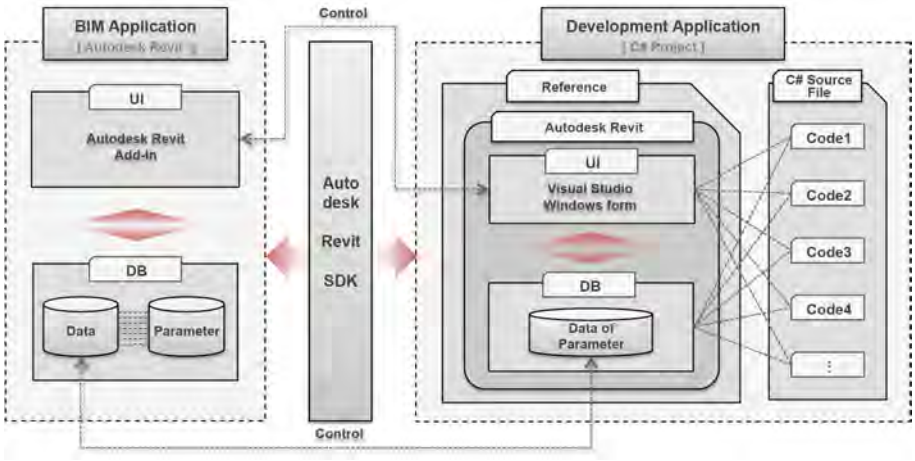


Figure 2. Development process of GCS .

4. G-SEED Certification Assessment BIM System Using GBT

This system must standardise the BIM library and information types and provide a consistent work environment for users to review the assessment result values and various alternatives quickly.

GBT is a green building information modelling template to obtain suitable outputs by building an environment that is linked to green building criteria automatically using BIM data.

4.1. FORMING GBT THAT IS A BIM-BASED TEMPLATE

figure 3 shows the structure of GBT and application of GBT(i) and GBT(o) to the BIM authoring tool. Users are provided with an installation file to run GBT.rte and GBT(o), which are template files of the BIM authoring tool in which GBT(i) is built. G-SEED assessment is carried out by modelling the library built in the GBT template and running GBT(o).

For automatic assessment in the GBT(o) environment, it is necessary to extract attribute data of the BIM model according to the assessment criteria. To assess nine items, mediating variables are set up to extract attribute data according to the assessment criteria in the nine libraries, as shown in table 4. Then, 14 list sheets are set up for the attribute data according to the mediating variables to be entered on GBT(o) automatically in a prompt and consistent manner. Users enter basic information in BIM add-in and enter the scores of 32 out of 41 items according to

the assessment criteria of the G-SEED manual. The nine items are assessed based on the attribute data, which is extracted automatically from the BIM model, and the scores of the 32 and 9 items are collected to come up with the final results of total scores and grades.

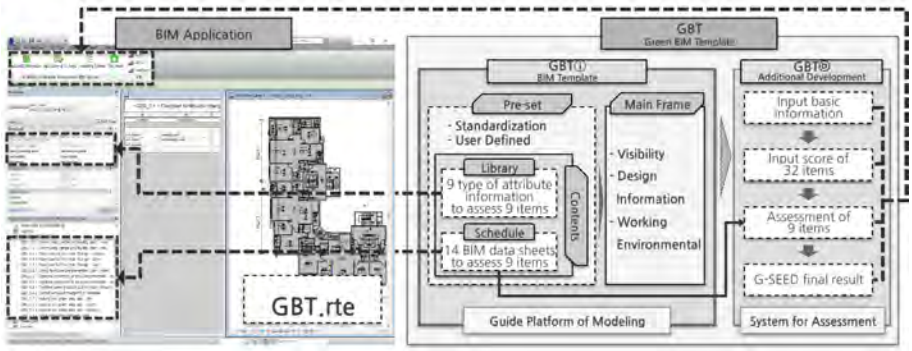


Figure 3. GBT structure and BIM authoring tool application.

4.2. BUILDING A LIBRARY FOR BIM-BASED CERTIFICATION ASSESSMENT

For BIM-based certification assessment, the library provided by the BIM authoring tool was used, and special facilities were added. An analysis of about 100 libraries built in the BIM authoring tool shows that the libraries consist of objects in the building, such as walls, doors, windows, components, pillars, roofs, ceilings, curtain wall system, curtain grid, and mullions. The libraries necessary to assess the nine items include topography, mass, pillars, walls, floors, doors, windows, rooms, and special facilities, as shown in table 4. Items, such as 3.4.1 and 3.4.2, are assessment of products that obtained green building and carbon labelling certifications, and thus must be used after the users choose and copy them according to library type.

Moreover, to extract attribute data complying with the assessment criteria for each item from the library, it is necessary to set additional mediating variables including the basic ones, as shown in table 3. To set the mediating variables, those that can be shared in multiple projects and libraries are created in the BIM authoring tool, and those necessary for each library are added to the projects, as shown in table 4. Here, the data of mediating variables are set as instance as attribute data varies according to whether there is non-bearing or bearing walls and the position of interior and exterior even if the same type of library is used.

The library with the mediating variables set up is built on GBT(i), and thus users can use the library to perform modelling and extract attribute data according to the mediating variables on a list, and enter the data on GBT(o) automatically to perform G-SEED assessment.

Table 4. BIM library and parameter.

Automatic Input Assessment List	Library	Parameter
1.3.1 Community center and facility plan	**site, mass**	facility name, area
3.1.1 Floor plan for life-style change	**column, wall, floor, door**	location(inside/outside), bearing/non-bearing, length
3.2.1 Living furniture use prevention plan	column, wall, floor, room	kind of room, area
3.3.1 Separate collection of recyclable material	mass, **special facility**	facility name, area, number of separate collection container
3.4.1 Certified green product use for valid resource recycling	column, wall, floor, door, **window**, etc	product name, certification, location
3.4.2 Carbon emission footprint of material	column, wall, floor, door, window, etc	product name, certification
6.1.2 Natural soil green area rate	site	name, area
7.1.2 Natural ventilation plan	column, wall, floor, window, **room**	kind of room, area, inside/outside, open/ shut, width, height, open area
7.3.3 Noise protection between units	wall	partition wall, wall material, width

4.3. G-SEED CERTIFICATION ASSESSMENT BIM SYSTEM USING GBT

Add-in of the BIM authoring tool of GBT(o) can be used in the BIM authoring tool when running the system installation file of GCS Setup.exe. The add-in of the BIM authoring tool is shown in figure 4.

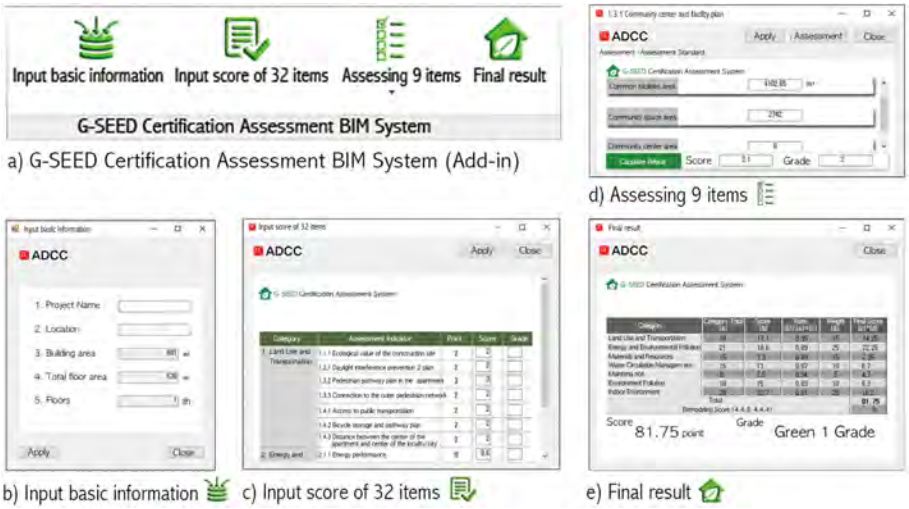


Figure 4. Interface of GCS.

5. Conclusion

The template for G-SEED certification assessment was established based on the results of this study, and the following conclusions can be drawn by proposing the BIM system.

First, there was a need for the library with necessary attribute data according

to the assessment criteria as well as the template that can extract attribute data promptly and consistently according to mediating variables for users to perform modelling for G-SEED assessment easily; the assessment was built with GBT.

Second, this study proposed the BIM authoring tool add-in system for users to perform assessment immediately after modelling in one BIM authoring tool and check the scores and grades promptly and objectively.

The limitations of this study are as follows. The developed BIM system can only assess in the unit of individual buildings. Thus, to assess multiple buildings within the complex, the final results could be drawn by calculating the assessment results of the buildings that exist in individual files manually.

Therefore, this study aims to provide users with a template that can assess multiple buildings in the complex in a single platform and support assessment items other than the nine items.

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INTEGRATION OF AN ALGORITHMIC BIM APPROACH IN A TRADITIONAL ARCHITECTURE STUDIO

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Abstract. Algorithmic BIM combines BIM and Generative Design (GD), merging the potentialities of both approaches. In this paper we describe the design process of a set of parametric facades developed using Algorithmic-BIM, and how this approach was integrated into the design workflow of two architectural studios. We demonstrate how the integration of GD together with BIM influenced the whole design process and also the selection of the final solution. Some of the limitations found during the entire process are also addressed in the paper, such as tight deadlines and financial constraints. Finally, we explain the pros and cons of using this design method compared to a traditional BIM approach, and we discuss the implementation of this paradigm in a traditional design practice. This work was developed using Rosetta, an IDE for Generative Design that supports scripts using different programming languages and allows the generation and edition of 3D models in a variety of CAD and BIM applications. The result of this work is an information model of three parametric facades for a residential building, from which we can extract material quantities and construction performance tests.

Keywords. Generative design; collaborative design; CAD-BIM portability; parametric facade design.

1. Introduction

Architectural practice is being redefined by the increasing use of BIM technologies, which have been replacing CAD tools at certain design levels. BIM allows architects to represent buildings' components in their 3D models, containing not only the geometrical information, but also the corresponding constructive information. As a result, the obtained models include all the building's information, which is important for the different specialities, and also for analysis and optimization processes during the design stage (Asl et al. 2014).

On the other hand, Generative Design (GD), a design approach that creates shapes through algorithms (Terzidis 2003), has been empowering architects' creativity by allowing the generation of several solutions in a short period of time

and the fabrication of highly complex projects that would be very difficult and time-consuming to produce manually (Kolarevic 2003). Initially, most GD tools were developed for CAD environments but there are already some extensions that allow the exploration of GD inside BIM tools, thus merging the potentialities of both approaches (Humppi & Österlund 2016) and allowing the emergence of a new design approach called Algorithmic BIM (A-BIM) (Feist et al. 2016).

This paper focuses on the integration of A-BIM into the design process of a traditional, BIM-based, architecture studio. To this end, we present a methodology for facade design using A-BIM and its evaluation in a real case where we collaborated with two portuguese studios (*Atelier dos Remédios* and *FOR-A architects*) that had no previous experience with GD and A-BIM.

2. Algorithmic BIM

Due to the changeable nature of architectural design (Bukhari 2011), architects require a design process that supports change. Unfortunately, traditional CAD tools require too much time and effort to modify designs and models, thus limiting the exploration of more intricate solutions. Nevertheless, recent technologies have already allowed the development and proliferation of more complex solutions, new patterns, and advanced fabrication methods (Kolarevic 2003). This includes GD, which is an approach to design that creates shapes through algorithms (Terzidis 2003). This approach requires the designer to develop an intermediate step between the idea and the design. In that step, the designer produces the algorithmic description of the intended design (Leitão 2013). It is this algorithm that, upon execution by a computer, creates the actual design.

When we combine GD with BIM-based approaches to design, a new paradigm emerges. This paradigm is named Algorithmic-Aided BIM (Humppi and Österlund 2016) or Algorithmic-Based BIM (Feist et al. 2016), and there are already some tools that support it: *Dynamo* (Autodesk 2015), *GenerativeComponents* (BentleySystems 2007), *RosettaBIM* (Feist et al. 2016; Ferreira & Leitão 2015; Lopes & Leitão 2011), *RhinoBIM* (VirtualBuildTechnologiesLLC 2015), and *Lyrebird* (LMNArchitects 2014) are examples that allow the exploration of algorithmic approaches inside BIM tools.

3. Case Study

The work developed in this paper is part of an architectural project authored by two portuguese design studios: *Atelier dos Remédios* and *FOR-A Architects*. The proposed challenge was to create a parametric facade for a residential building in Lisbon that ensured different degrees of permeability, with one important limitation: the solution had to be developed in six days. As both design studios required the final model in *Revit*, we decided to develop the design using an A-BIM approach.

The project consisted in a residential building for the urban area of Belém, in Lisbon. The intervention lot had a pre-existence that had to be maintained during the development of the new project (figure 1.A), which was then incorporated into the building's main facade, the one facing the main street.

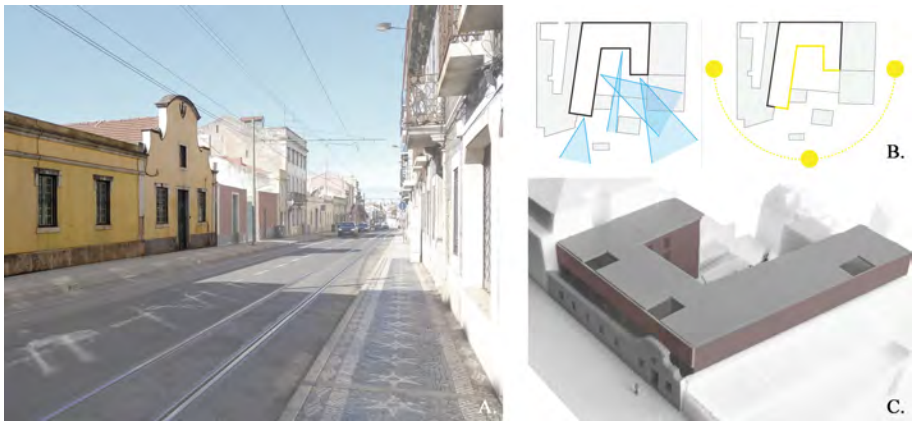


Figure 1. A - View of the intervention lot; B - Dwellings' views and natural light analysis; C - The building's physical model with the developed facades in colour.

The building had a *U* shape in plan to create a central courtyard that provided natural light and pleasant views to all the dwellings (figure 1.B).

The proposed challenge was the development of three parametric facades for the residential building (figure 1.C). The idea was to create an architectural envelope that would be more or less perforated depending on the type of function of the space associated. When the facade coincided with the dwellings' terraces it should be more permeable. When the facade corresponded to more private areas, i.e. bedrooms and kitchens, it should be less permeable or totally opaque. Initially, this concept *permeability-opacity* was left open, allowing us to explore a range of different solutions. The architects could then evaluate the proposed solutions and suggest improvements. This resulted in a dynamic design process with the direct participation and feedback of both parties.

4. Methodology

We started by implementing an algorithm that addressed the architects' idea and the information related to the project. Then, new parameters and relations between parameters were added to the algorithm in order to produce different facade patterns. Since there was no decision regarding the material to be used at this design stage, the developed solutions took advantage of different materials, such as brick, tiles, etc, creating different strategies of permeability. After analysing the range of proposed solutions, the architects decided to combine features of two designs (figure 2.A-B), using bricks of different sizes placed in order to create random protrusions and also casual voids, i.e. brick absences (figure 2.C). It is important to note that this is the type of solution that few people are willing to produce manually, especially with the existing time constraint.

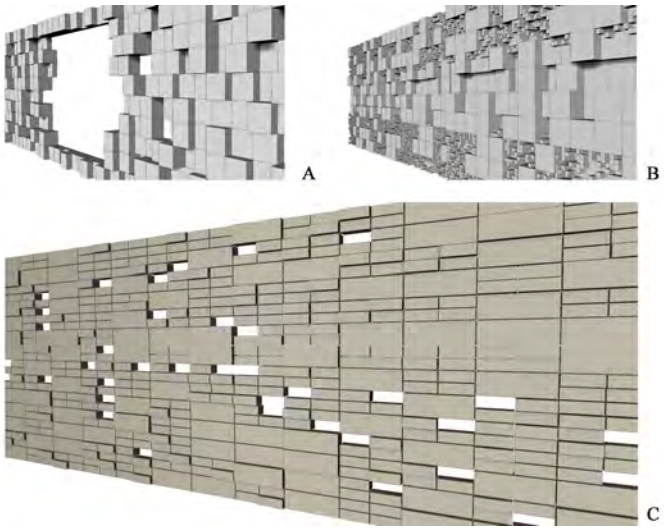


Figure 2. Some of the ideas developed at an initial design stage (A and B); C shows the obtained facade pattern at a final stage.

With the aim of achieving a higher control over the feasibility and cost of the final solution, the architects suggested a rationalization of the design, reducing the degree of variation of the final pattern. As a result, although the initial designs, exemplified in figure 2.A-B, were composed by elements with different protrusions, this variation was reduced to only two possible protrusions. Similarly, the bricks sizes were reduced to only two, wherein the bigger bricks (60x5x20cm) had four times the size of the smaller ones (30x5x10cm). Lastly, the architects decided that facade voids should only be created by the absence of small bricks. The choice between placing one large brick or four small bricks was randomly controlled, as was the creation of a void and the placement of a protruded brick.

To sum up, the architects' idea was to maintain the initial concept of randomness and irregularity, but with more restricted design variables. Figure 2.C is a conceptual representation of the pattern that was achieved after implementing all suggestions. The following stage was the generation of a more detailed model adapted to the building's dimension and to the areas with different permeability degrees.

Compared to a traditional modelling approach, one of the advantages of using an algorithmic approach is the ability to implement changes more rapidly during the design process, allowing us to obtain improved results with much less effort and time. In this case, the architects could instantaneously visualize the resulting models right after the implementation of their feedback. Similarly, it also allowed the application of increasingly small design changes in more advanced design stages, thus enabling a step-by-step improvement of the models until the architects' goals were completely reached. Figure 3 represents some of the variations that were applied to the pattern, which included (1) the balance between the placement of a large brick or a set of four small bricks, (2) the percentage of

protruded bricks, and (3) the degree of the facade's permeability in certain areas, i.e. the percentage of absent bricks.

Finally, as the set of parametric facades was directly generated in *Revit*, these were easily incorporated and correctly placed in the final model. As a result, the BIM model was thus completed with the correct BIM elements/families and construction information.

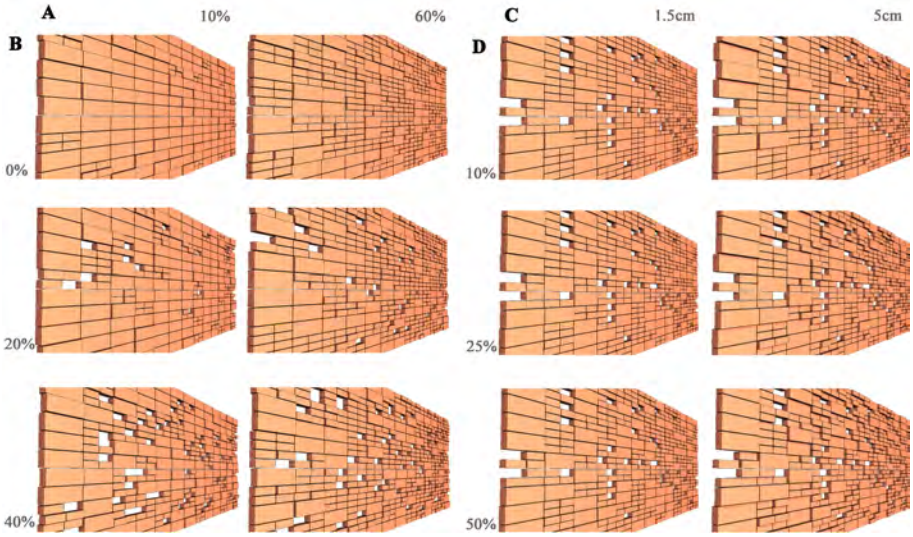


Figure 3. Design Variations: A - Percentage of four small bricks; B - Percentage of absent bricks; C - Protrusions' depth size; D - Percentage of protruded bricks.

5. CAD / BIM Portability

The work presented here was developed using *Rosetta* (Lopes & Leitão 2011). One of the advantages of this tool comes from its emphasis on portability between CAD and BIM tools. As we had only six days for the development of the facades, each of the stages described previously had to be very short. Therefore, it was important to quickly generate different design solutions. Given that CAD tools are typically more efficient than BIM tools, we took advantage of *Rosetta*'s portability to test our algorithms using *AutoCAD* or *Rhino*. When we had a design ready for evaluation by the design studios, we used the same algorithms to generate the model in the BIM tool without any extra effort (figure 4), thereby avoiding spending time redoing the model from the scratch. The resulting BIM model had the corresponding BIM families, construction information and correct dimensions to be directly incorporated in the 3D model of the whole building developed by the design studios. The only required step was to place it in its correct location (figure 5).

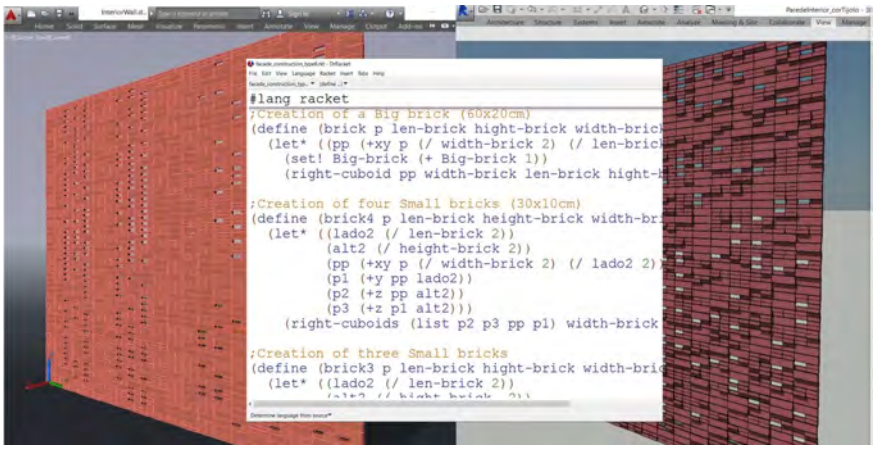


Figure 4. The visualization of two models generated in different tools with the same algorithmic program: AutoCAD on the left, Revit on the right, and Rosetta IDE at the center.

6. Manufacturing Stage

The next stage was dealing with the construction rationalization. As the budget for this project was relatively low and the availability of advanced manufacturing processes was limited, it was important to find a balance between the different manufacturing strategies in order to solve the existing constructional issues. The bricks used in this facade had a non-conventional size and so they had to be pre-fabricated. In order to reduce the production cost of these customized bricks, the architects had already limited the number of different brick sizes to only two. Nevertheless, one of the greatest challenges found during this stage was the placement of the bricks since several characteristics of the produced pattern were controlled by random factors: (1) The decision between placing a large brick or four small bricks; (2) The selection between two different positions for the placement of each brick; (3) The location of the facade voids.



Figure 5. Rendered views of the building's final model. On the left: view from the main street where two of the developed facades are visible; On the right: view of the building's inside courtyard with the third facade.

6.1. CONSTRUCTION RATIONALIZATION

At this stage, the first limitation found was the depth of the bricks, which was too narrow to obtain the necessary stability when stacked. In order to overcome this situation, the architects decided to double this dimension.

Another limitation was the existence of small bricks immediately above a facade void, which meant these bricks would have no support. One possible solution was regenerating the facade models with an additional constraint to only place large bricks on top of facade voids. However, this would decrease the degree of variation of the pattern. Another possible strategy was to fabricate the sets of three or four small bricks as single units. This created another challenge, which was how to fabricate the smallest number of different molds while maintaining the facade pattern complexity and randomness. Fortunately, as the back face of each unit of bricks had the front pattern inverted, we could horizontally and vertically rotate them to obtain different patterns. Figure 6 shows some of the typologies created for each unit of small bricks and their corresponding variations.

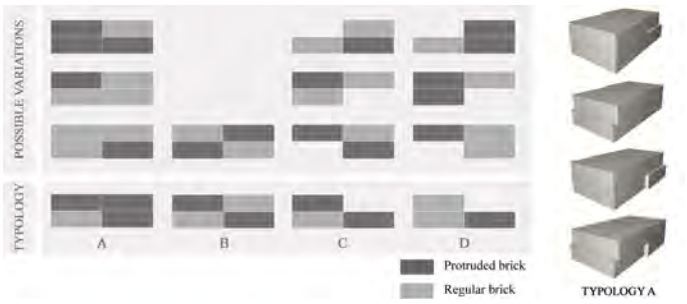


Figure 6. On the left: Four typologies developed (A-D) with the respective variations that each one produces when rotated; On the right: typology A in 3D model.

6.2. THE PLACEMENT OF THE BRICKS

For the placement of the bricks on site, we merged two approaches: the use of metal profiles to maintain the verticality of the stacked bricks and the application of angle brackets to fix the bricks to the building's wall. These elements were also algorithmically developed, which allowed us to adjust some details in order to minimize material waste and improve the facade stability and ventilation.

Our solution required the creation of four small grooves on each brick to then place the metal profiles. These would be centred and distanced according to the protrusions dimension so as to allow the placement of the bricks in two different positions: when placing a protruded brick, the below and above metal profiles fit the first grooves. Otherwise, they fit the second (figure 7.A). This process is repeated at each level of bricks and, simultaneously, some mortar is added to glue the bricks together. Additionally, in order to give stability and fix the bricks structure to the facade wall, we decided to use angle brackets to hold alternating rows of bricks (figure 7.B). The obtained solution also had the advantage of creating a thermal isolation zone between the bricks structure and the facade wall, which is visible in figure 7.C.

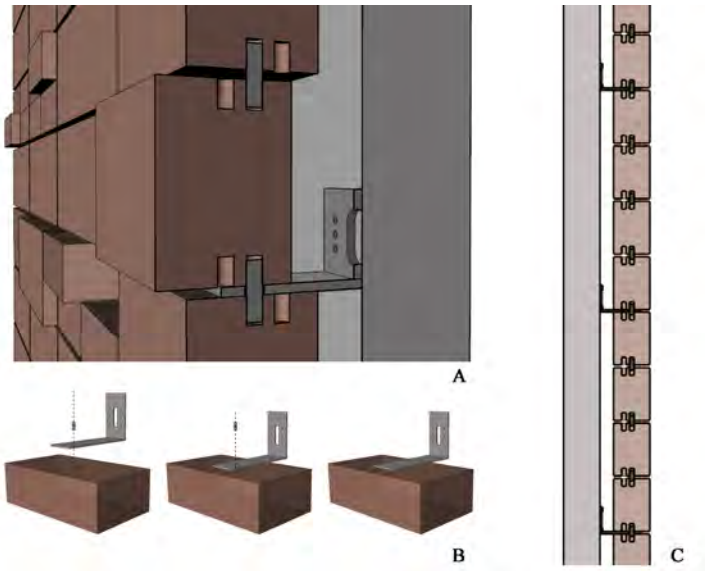


Figure 7. A - A facade section showing how the brick grooves create different brick placements; B - The fitting process of the angled brackets and metal profiles; C - A section of the facade model showing the thermal isolation zone.

For both cost estimation and the following manufacturing stage, it is important to have the list of quantities of all the facade elements. However, due to the complexity of the design, tallying is not trivial and it is difficult to get this information from tools such as *Revit*. To overcome this problem, we extended our algorithm to include the tallying process. As an example, figure 8 shows the exact quantities of each brick typology that was used.

Finally, having the 3D model of each set of moulds, metal profiles and angle brackets, and the constructive information about each element's position, material, and dimensions, the design studios can proceed with the fabrication of the required elements and with the construction of the facade.

7. Evaluation

The case study presented in this paper demonstrated how the application of the A-BIM approach in a traditional architectural studio supported the architects with a more flexible design process. Moreover, the example also showed how this approach allowed the architects to develop the desired facade solution in a very short amount of time. It is important to note that, due to the tight deadlines (six days) of this project, the use of a traditional approach might not have enabled the development of the obtained final solution. Firstly, because it would be tiresome and would take much more time due to the complex nature of the design. Secondly, the obtained model would not be flexible enough so as to allow the incorporation of design changes. The A-BIM approach allowed the incremental improvement of the obtained designs by including the architects' feedback almost immediately,

thus enabling the quick visualization of new results.

Additionally, the A-BIM approach enabled the generation of the algorithmic facade model directly in *Revit*, the BIM tool used by the architects. The resulting model included the corresponding BIM information and it facilitated the exploration of the manufacturing stage. In the end, the final model was further developed in order to include several construction elements. This allowed the architects to have a model with the elements' information (i.e., dimensions, material quantities, prices, etc.) necessary for the construction stage.



Figure 8. The bricks typologies and the number of times each one appears.

8. Conclusion

Only recently were both the BIM and GD paradigms combined in the development of architectural models, allowing architects to take advantage of both approaches during the design process. In this paper, we described the design process of a set of parametric facades which were developed using A-BIM, an algorithmic-based process for BIM, and how this approach was integrated into the design workflow of traditional studios. We also demonstrated how the integration of GD together with BIM influenced the whole design process, the selection of the final facade design, and the rationalization of the design for the construction. Additionally, we addressed how we dealt with some of the limitations found during the entire process, including tight deadlines and financial constraints. Finally, we explained the pros and cons of using this design approach compared with a traditional BIM approach, and we discussed the integration of this paradigm in the traditional design practice.

This work was developed using *Rosetta*, a programming environment for Generative Design, which supports scripts written in different programming languages that can generate identical models in different CAD and BIM applications. In the paper, we also demonstrated how this capability was fundamental for speeding up the entire process, as it allowed us to experiment with designs using efficient CAD tools and, when satisfied with the results, to quickly switch to the BIM tool used by the studios.

Acknowledgements

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WHERE AM I?

Spatial Cognition Inside Building Information Models

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Abstract. How do we know what we are looking at while viewing inside Building Information Modelling (BIM) models? Current architectural software typically provides disconnected methods of aiding spatial cognition. There is a strong history of navigation tools developed for controlling our exploration and movement in BIM models, a study by Ruby Darken and John Sibert (1993) found these tools had a strong influence on people's behaviour and understanding of digital space. People perceive and navigate space differently depending on their individual experience with a BIM model, designers and architects build up a detailed cognitive map during the design of a project, while other people have a less detailed comprehension of a project, having only been exposed to select views. This paper will outline key strategies to improve how people comprehend digital space, supporting people in understanding distance and size while inside BIM models. Three design research projects will be presented. The result of the projects define three strategies; Architectural wayshowing, interior-aware transitions, and distance confirmation. Architectural wayshowing needs to be implemented during the design phase, while the remaining two need to be introduced into BIM editing and viewing software.

Keywords. Whiteout; wayshowing; spatial cognition; navigation; BIM.

1. Introduction

Building Information Modelling is employed across all stages of architectural production. While BIM provides many benefits (Eastman et al. 2011), navigating around the model is still problematic, resulting in frustration and inaccurate spatial cognition. People often become 'lost', even experienced BIM operators, inside a model (Dodiya & Alexandrov 2008; Kopper et al. 2006) causing an "unproductive and unpleasant experience, even when trying to do the most basic three-

dimensional navigation operations" (Fitzmaurice et al. 2008, p. 7). These experiences of becoming 'lost' inside BIM models are similar to experiencing whiteout conditions, the loss of clues that we use to spatially orient and locate ourselves, that arctic explorers face. Explorers of BIM models become confused and frustrated when confronted with whiteout conditions.

The aim of this research is to examine methods of improving spatial cognition through aiding navigation inside BIM models. This research sets out to advance navigation of BIM models to expand people's spatial cognition in improving design, construction and building operation. Typically the design team have a resolved cognitive map of a BIM model due to their involvement in a building project, however many others involved have a incomplete or even incorrect understanding of a proposed building.

Navigation can be defined as the action of determining your position and direction allowing movement to another location. Another more useful definition, that of Professor of Computer Science Laura Leventhal, is "navigation is the cognitive process of acquiring knowledge about space, strategies for moving through space, and changing one's meta-knowledge about space." (Jul & Furnas 1997). Through the act of navigation one creates a cognitive map of space they move within. This is straightforward with viewing an object, such as orbiting around the exterior a building,. Once digitally inside a complex space, such as the interior of a building, all the clues from the external environment are lost. The standard navigation tools: orbit, pan, etc are less useful inside, even the walking tools are frustrating.

In his book The Lost Art of Finding Our Way, Professor John Huth states that "all navigational cultures have to deal with similar challenges: spatial orientation, the ability to estimate distances and find position from environmental clues" (Huth 2013, p. 8). These three challenges are still the case inside BIM models, while research has provided solutions for aiding spatial orientation and location identification (Chittaro & Venkataraman 2006; Dodiya & Alexandrov 2008; Ruddle et al. 1997) There has been very little research of or support for helping people understand distance inside BIM models (Interrante et al. 2006; Leyrer et al. 2015; Ries et al. 2008; Turner & Turner 1997), these papers highlight that people underestimate distances inside digital space, they do not offer any methods of supporting or aiding people in helping to estimate distance with more accuracy to improve spatial cognition.

To move within BIM models, where moments of whiteout are common, we need to navigate the unknown. John Huth's (2013) three elements of navigation give clues to aid experiencing BIM models. I believe that spatial orientation (Fitzmaurice et al. 2008; Ziemek et al. 2012) and location awareness (Luo et al. 2010) have adequate solutions already, although whether they are being utilised is beyond the scope of the present research. In contrast, the estimation of distance inside BIM models is poorly supported, which suggests that aiding distance cognition will improve navigation and reduce moments of whiteout.

When viewing a BIM model, predefined views have commonly been created, based either on major drawing projections such as plans, sections, elevations, and perspective views or on clashes detected and requiring resolution. Some software provides a spatial transition between the defined views, whereas others jump in-

stantly between views. The spatial transition helps orient and locate people if the correct transition is used. What is not clearly represented is the distance travelled between views. Knowing the distance between views helps in building an accurate cognitive map. These transition function by treating the model as an object, ignoring the interior layout of a building.

The term wayshowing refers to the activity of planning and implementing orientation systems in buildings and outdoor areas, this often incorrectly described as 'wayfinding' (Mollerup 2013). People have always practiced wayshowing by leaving clues, marks, or signs. Wayshowing and wayfinding relate to each other like cooking and eating. Wayshowing proceeds and enables wayfinding. "Wayfinding is what we do when finding our way around unknown quarters. Good wayshowing is user-led, built on how we practice wayfinding" (Mollerup 2013, p. 6).

As digital workflows encompass virtually all stages of architectural production knowing what and where you are inside digital models becomes critical. The paper will outline three key strategies that help reduce moments of whiteout and improve spatial cognition.

2. Method

The research covered in this paper is positioned as research by design practice, a reflection-in-practice process of designing via making, based on what Donald Schön considers designing as a reflective conversation with the material of a situation (1983). Practice as creative-making activity is an "explicit and intentional method for specific research purposes" (Gray & Malins 2004, p. 104) through design and reflection. The process of reflection is embedded within the projects, which were evaluated during the designing, making, and testing, thereby informing the next project.

Exploration of possible research instruments exposed the limitations of those used by Doug Bowman et al. (Bowman et al. 1998), including that a memory task for information gathering within an immersive virtual environment may not give a clear response of the navigation modes. Sketching cognitive maps was rejected because a cognitive map is constructed of multiple sensual inputs that are impossible to capture in a sketch-which typically defaults to a plan and can be limited by people's perceived drawing ability. Spatial cognition is manifest in an individual mental image or cognitive map and requires all of our senses, it is not completely understood (Montello 2001; Tversky et al. 1999; Waller & Nadel 2012).

Different research instruments (Wilkinson & Birmingham 2003) are used across the projects, they are case studies that employ observation, a questionnaire, and critical reflective research methods. Using a questionnaire in the Te Ara Hihiko project provided qualitative responses to wayfinding tasks, asking people to rate spatial awareness with different navigation support provided while searching for different locations within a BIM model. Te Ara Hihiko project used the work of Bowman, D. A. et al. (1998) paper A Methodology for the Evaluation of Travel Techniques for Immersive Virtual Environments, allowing a range of criteria across different conditions to be evaluated.

The concept of whiteout is the base criterion used in evaluating the project work: how does each project improve spatial cognition and reduce the incidences of whiteout inside BIM models? To understand a building spatially, we need to experience moving inside the structure. Whiteout moments are the times you become stuck while experiencing the model, the information you want is obscured, often resulting in frustration and misunderstanding of the model.

3. Projects

The projects provide explorations of assistive interfaces for spatial cognition and awareness that aid in the estimation of distance within BIM models. Previous research has focused on unaided experiments in virtual environments of distance estimation (Interrante et al. 2006; Ries et al. 2008; Turner & Turner 1997). The projects in the present research explore methods of assisting people to improve distance and scale awareness, each project investigates methods of aiding distance awareness: Te Ara Hihiko critiques the mouse walk tool by providing different levels of guidance; Odograph records and displays total and last distance travelled, aiding in the spatial comprehension of a building; Your Grid develops a spatially aware personal grid that is overlain at current floor level, aiding distance estimation. All three projects interrogate methods of aiding spatial cognition via improving distance comprehension. Each project tests the implications of different modes of understanding distance.

3.1. TE ARA HIHIKO

Te Ara Hihiko is māori and translates as The Creativity Path, this project investigates the functionality of the mouse walk tool against different levels of guided navigation. This was done by tracking the orientation and wayfinding of 12 participants exploring a three-dimensional BIM model given three tasks. A call was made to a local Revit users group for participants, allowing for experienced users, use to working in complex BIM models .The following performance metrics: Ease of Use, Spatial Awareness, and Information Gathering were selected from Professor Bowman and co-workers paper entitled ‘A Methodology for Evaluation of Travel Techniques for Immersive Virtual Environments’ (1998) to help explore the question of how spatial orientation and an understanding of location can be improved in BIM models.

The project explores three travel techniques, Mouse to Walk with recommend AI interior-aware path to follow and automated interior-aware AI generated transition. The former technique responded to the current standard CAD/BIM software mouse command of click and drag to ‘walk’. People were limited to this method of movement in order to explore how they use this often-under-utilised tool. A ‘look’ command was also provided. The second techique, free-form travel was supplemented with a guided or recommended dynamically created AI path. The third travel technique was a fully automated AI directed path that takes the participant on a completely guided walk or interior-aware transition to the specified location.

The guided AI system leveraged the Unity AI pathfinding technique that dynamically generates a line showing the shortest walkable path to the target room's location. An invisible controller is spawned at the participant's location; the invisible controller then travels to the target location at walking speed, leaving a coloured graphical line showing the path. The intention is for the participants to follow this line as it travels towards the target.

The three tasks were designed to get the participants to find given locations via different navigation methods. The tasks provided movement across multiple levels and different types of spaces that most participants would not have previously entered or known of in the physical building. Task one used only standard mouse-controlled walking and looking tools, with the participants' current room and level information being given in the top-left- hand corner of the web player frame (figure 1). Task two used the same navigation tools and current location with an AI trail to follow. Task three was an AI-generated auto-walk option that guided the participant automatically to the destination. The tasks were as follows:

- Task 1: navigate to room Studio D (a large open space on Level D)
- Task 2: navigate from room Studio D to Studio B (a small studio space on level B).
- Task 3: navigate from Studio B to the studio E on Level E.

At the completion of all three tasks participants were asked to rate the following criteria:

- Ease of Use: How easy did you find navigation for task 1?
- Difficult 1 2 3 4 5 Easy
- Spatial Awareness: How well did you know your position and orientation during and after task 1?
- No idea where I am 1 2 3 4 5 Know exactly where I am
- Information Gathering: How perceptive of the building were you while moving for task 1?
- Unperceptive 1 2 3 4 5 Very perceptive.

3.2. ODOGRAPH

This project aimed to provide a clear method for measuring how far the user has travelled since their last resting place, and if the destination is predefined, to display the distance remaining to travel in real time to help build a scaled cognitive map. The concept behind providing distance information is to help draw connections across a digital model so that we can develop correct relationships between spaces and views of the model, thereby developing spatial awareness. Odograph sets out to accurately aid distance estimation while navigating inside a BIM model, displaying the total distance travelled, the last distance travelled, and indicating whether the user is moving or still (figure 1). By providing an accurate gauge of the total distance travelled, the scale represented by a model can be understood. Although a trained architect may know this intuitively, it is not always the case. People without the spatial training of an architect or builder experience models with a different understanding of spatial scale. This is similar to the way in which

many people are unable to understand architectural drawings. A more immediate distance cognition is the distance a user has travelled from their last resting location, and allows a quick assessment to be made of the distance between two rooms or the length of a single space. These distances help to build a scaled cognitive map of a building model by quantifying an experience that is typically forgotten about. The interface also displays whether the user has paused long enough (or not) to trigger a new segment of measurement, indicating a break between distances.



Figure 1. Odograph records and displays the user's total distance and last distance travelled, to allow correct comprehension of the scale of a building.

3.3. YOUR GRID

Grids are "one of the oldest architectural design tools" (Gross 1991, p. 33), and have been and continue to be used for designing the location of architectural elements. At some point in the late nineteenth or early twentieth centuries, a datum matrix became a convention for locating a dimensional reference system or what is commonly referred to as the column grid or building grid. This grid establishes a datum for major structural elements and can be represented in plan, section, and elevation views. The column grid is a powerful ordering device and important locating mechanism, often the key origin device in plan drawings that functions when an overview is possible. When inside a BIM model, the column grid is usually obstructed or not visible at all. Related to the (lack of) visibility of the column grid is a lack of a consistent distance between lines, due to the relationship of the column grid to the building structure. With architectural drawing sets, a clear order of view and context is constructed from plan views, elevations, and sections, down to details. The plan or section provides the overarching context, but such context can be easily lost inside a BIM model. With respect to spatial cognition, these lim-

itations can confuse a person viewing the interior of a model. The premise of Your Grid is to provide a standard one-metre grid that is located between the viewer's position and the nearest floor level. The project seeks to provide an egocentric one-metre square grid that can be used to gain a sense of scale (figure 2). The grid is centred on the viewer to quickly give the correct size of what is currently being viewed, either an exterior view, or a tight interior view of structural elements. Your Grid can be configured to appear only while still or to follow the viewer as they navigate through space. Once stationary, users are able to adjust the grid's rotation to allow it to align with key elements.

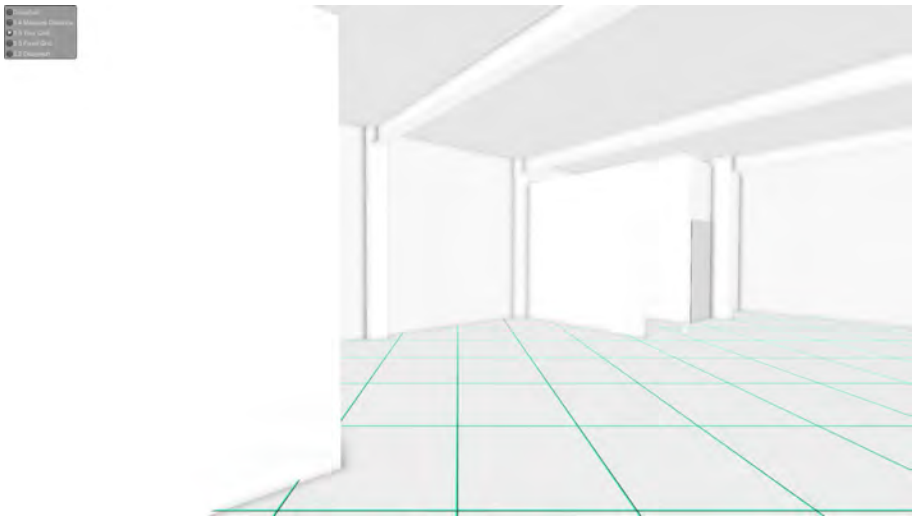


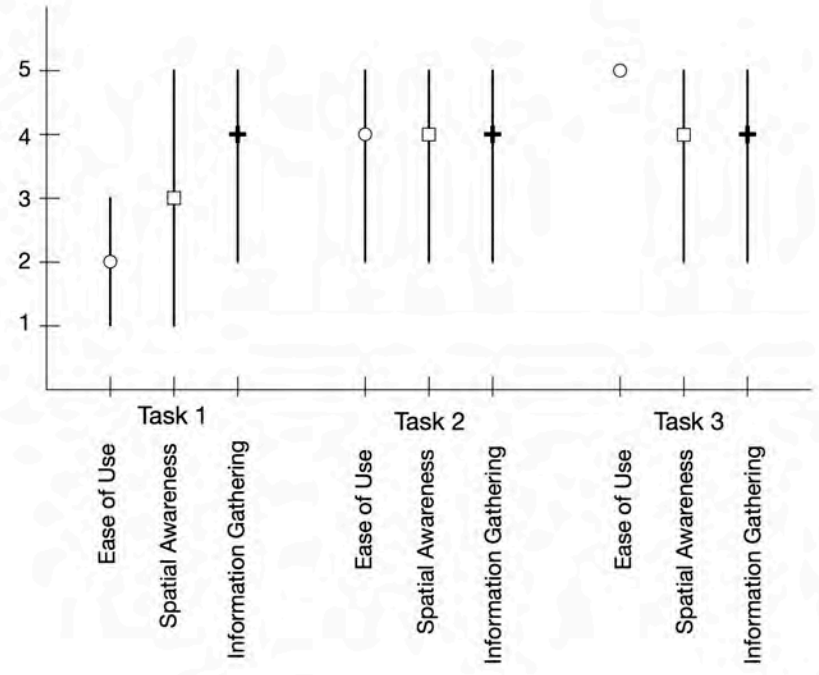
Figure 2. Your Grid locates a 1-metre grid at the nearest floor level to the user's location, which can be rotated to align with their view. The grid can be set to appear only while stationary so as to enable unobstructed navigation.

Your Grid differs from existing grids in three-dimensional software, which are oriented around the origin of the digital environment (0,0,0). Once inside a building model, these grids are obstructed, rendering them ineffective in aiding spatial cognition. Autodesk proposed a smart multiscale reference grid (Glueck et al. 2009), which also stays fixed around the origin plane, responding to the scale of what is being viewed (for example, drawing the grid at millimetre intervals when viewing a small object or at kilometre intervals when viewing a city). Your Grid is set at a constant scale, a metre grid, a building scale, which allows a viewer to quickly understand what is being viewed. When a viewer is focused on a detail, it quickly becomes clear that the view is scaled under a metre, or looking out across an open room the size can be estimated by counting the grid lines. Your Grid provides a frame of reference to understand the scale of what is being viewed. This contrasts with the observation that "typical three-dimensional software applications do not account for the scale of the environment within their navigation tools" (McCrae et al. 2009, p. 7).

4. Results

Although "there is no one proper way to navigate" (Huth 2013, p. 8), an understanding of distance helps to appreciate the complex behaviour of navigation. We all have different abilities of navigation and spatial cognition that impact on our experience inside BIM models. The navigation tools that allow us to explore inside digital environments also influence our experience. I explored the mouse walk tool by testing three levels of aiding location-finding. The aided pathways, which highlight the benefits for spatial awareness and the improved ease of use of location-aware relative distanced paths, assist people to spatially understand a BIM model. With further explorations of aiding distance estimation, the projects of Te Ara Hihiko, Odograph, and Your Grid, demonstrate enhanced methods of supporting spatial cognition within the interiors of BIM models. These projects began to establish an important area, that of aiding distance cognition within BIM models, reducing whiteout moments, each project offers a specific identification of distance, Odograph allows understanding of distances travelled benefiting comprehension of scale between rooms, Your Grid provides a spatial grid that intuitively shows the scale of a room.

Table 1. Te Ara Hihiko ease of use, spatial awareness, and information gathering range and average responses for each task.



Reflecting upon the projects resulted in the importance of how the design of a space impacts the wayshowing experience, users of a building build up a cognitive map while exploring it, considering the first person architectural wayshowing. Designers can leverage the first person view within BIM models to develop ways of architectural wayshowing to help people finding their way. Currently BIM software either moves instantly to different views or transitions with no understanding or respect of the architectural design and context. By adding spatial transitions that actively respond to floors and walls, allowing people to experience the building design, helping to build a correct cognitive map. Interior-aware transitions would help people understanding where they are and what they are looking at with in the model.

5. Conclusion

Navigating the unknown is hard. Navigating within unknown BIM models is harder. In my research, I sought new approaches to design methods of navigating BIM models to gain enhanced spatial cognition. Using a reflective practice methodology of project-based design investigations, the research explores aiding distance estimation and wayshowing methods that allow spatially aware navigation tools to reduce moments of whiteout.

The architecture and construction industries are in transition from a two-dimensional workflow to multidimensional data-driven processes. I argue the need for advanced navigation tools in this transition to improve people's' spatial cognition. Three projects investigated methods of improving spatial cognition inside BIM models, Te Ara Hihiko, Odograph, and Your Grid. Each project investigated different methods of aiding, AI pathfinding, distance traveled and a view user centric grid. The results of these projects distilled three strategies to improve spatial cognition; assistive interfaces, architectural wayshowing, and spatial transitions.

Future research needs to address virtual reality VR and augmented reality AR and how methods of navigation can help improve spatial cognition. Currently VIVE headset and controls allow people to jump to new location, this allows an intuitive method of navigation, it is still spatially confusing. John Bowman stated "that jumping techniques can reduce the user's spatial awareness" (Bowman et al. 1997, p. 51).

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Digtal Scanning and Point Cloud Modelling

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CONSTRUCTION SITE MONITORING USING UAV OBLIQUE PHOTOGRAMMETRY AND BIM TECHNOLOGIES

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Abstract. Traditional construction site monitoring primarily relies on a human presence. Automated construction progress monitoring is expected to make this process much more efficient and precise. The planned state of construction (as-planned) must be validated by the actual state (as-built) during automated construction progress monitoring. This research uses an integrated application of high-resolution low-altitude UAV (Unmanned Aerial Vehicle) oblique photogrammetry and Building Information Modeling (BIM) technologies for construction site management. A case study was carried out for a renewable energy development program in the JiaDing District of Shanghai, China. A high-resolution 3D model of the construction site acquired by our multi-motor UAV provides data to illustrate the as-built state of the construction program. Comparison of the UAV-based 3D model (as-built) with the BIM-based 3D model (as-planned) for a specific chimney was used for dynamic construction site monitoring. Our results show 3D illustrations of construction progress. This research demonstrates that the BIM technology in conjunction with the use of UAV photogrammetry provides efficient and precise as-built data collection and illustration of construction progress.

Keywords. Oblique Photogrammetry; UAV; 3D modeling; BIM;

construction site monitoring.

1. Introduction

Construction site monitoring is a time-consuming and primarily manual process where there is a great need to implement automation. Automated construction progress monitoring compares the as-planned state and the current built state to monitor progress and detect deviations during construction (Tuttas et al. 2015). Building information modeling (BIM) technology is a very useful tool for all phases of a construction project. Used as a source of as-planned information, a BIM model provides accurate 3D illustrations and is used to effectively monitor work progress through the entire lifetime of a construction project (Vacanas et al. 2016). Low-altitude UAV (Unmanned Aerial Vehicle) photogrammetry, a new rapidly developing technology, is able to collect the as-built information in a cost-effective and efficient manner (Achille et al. 2015). Oblique aerial photogrammetry (Svennevig et al. 2015) enables image collection from different angles during flight, thus providing fast and efficient access to information and the extraction of different facades of urban buildings. The 3D model generated shows detailed structures and real textures, resulting in a high-precision model.

This research used the integrated application of high-resolution low-altitude UAV oblique photogrammetry and building information modeling (BIM) technologies for construction site management. First a UAV oblique photogrammetry survey was conducted to acquire a high-resolution 3D architectural model of the construction site. Then, the UAV-based 3D model (as-built) for a specific tower was compared with the BIM-based 3D model (as-planned) for dynamic construction site monitoring. Progress at the construction site is quantitatively evaluated, and the capability of the integrated application of high-resolution low-altitude UAV oblique photogrammetry and building information modeling (BIM) technologies for construction site management is fully demonstrated.

2. Methodology

Low-altitude UAV oblique photogrammetry is a rapidly developing new technology. Traditional 3D model construction primarily relies on manual photography to retrieve the structure and textures of architecture and consumes time and labor. Because of the complex production process, high cost and rough generated model, traditional 3D model construction cannot satisfy the needs of large-scale 3D modeling of a smart city. Compared with traditional aerial photography, UAV photogrammetry is less affected by weather conditions, low flight altitude, limited airspace and cost. As a new aerial photogrammetry platform, UAV can quickly and efficiently obtain high-quality and high-resolution images. The rich texture information provided by UAV photogrammetry is particularly helpful in generating high-accuracy 3D architectural models.

Aerial ortho photogrammetry can only capture the ground from the vertical angle. The low-altitude UAV oblique photogrammetry in this study can capture images from different perspectives by using multiple sensors on the same UAV platform. This system quickly and efficiently obtains abundant data information

and different façades of city buildings conducive to the detailed 3D modeling of a smart city. The texture information acquired from this platform is true and reliable, and the architectural model is precise and detailed.

2.1. LOW-ALTITUDE UAV OBLIQUE PHOTOGRAMMETRY WORKFLOW

To conduct low-altitude UAV oblique photogrammetry, flight preparation, route planning and camera calibration should be carried out in advance. A multi-rotor UAV is employed to capture the ortho and oblique images during the flight. When images are acquired, rectification is conducted using optimized internal camera parameters. An image matching procedure is carried out to provide adequate 2D key points for aerial triangulation photogrammetry processing. Then, point cloud densification is conducted for mesh generation, and texture rendering is employed to finally achieve the comprehensive 3D model. The complete flow chart is shown in figure 1.

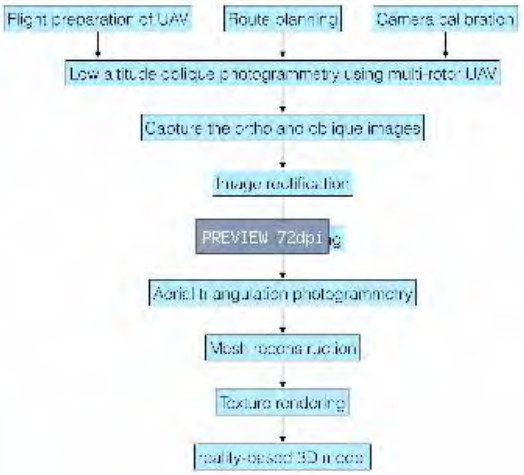


Figure 1. The flow chart of low-altitude UAV oblique photogrammetry.

3. Generation of 3D Model Based on Low-altitude UAV Oblique Photogrammetry

The construction site is located at the Town of Gutang in the Jiading District, Shanghai, China. This site is a Renewable Energy Development Program that receives substantial attention from the government of Shanghai. Thus, it is a key project of Shanghai and the number one project of the Jiading District. The size of the construction project is 46475 m^2.

3.1. UAV OBLIQUE PHOTOGRAMMETRY SYSTEM

The multi-rotor UAV (figure 2a) we used in this research is designed for aerial flight at an altitude of 100 to 300 meters. The UAV is equipped with a 5-lens camera with one nadir and 4 oblique views that is able to capture images from

five different angles (figure 2b). The view angles of the four oblique lenses are 45 degrees. GPS and IMU instruments are also mounted to acquire the geographical location and attitude information at the time of exposure.



Figure 2. a) The multi-rotor UAV equipped with a 5-lens camera. b) A set of exposure images at a certain point in time.

3.2. FLIGHT ROUTE PLANNING

The flying altitude was 100 meters. The ground resolution of images acquired is 2 mm/pixel with a 70% course overlap and 50% side overlap. Figure 3a illustrates our flight route planning, and Figure 3b demonstrates the ortho mosaic image of the whole study area. Images acquired from multiple perspectives avoid the shot block problem that occurs during traditional aerial photography. The textures of different facades are also collected perfectly during the flight.

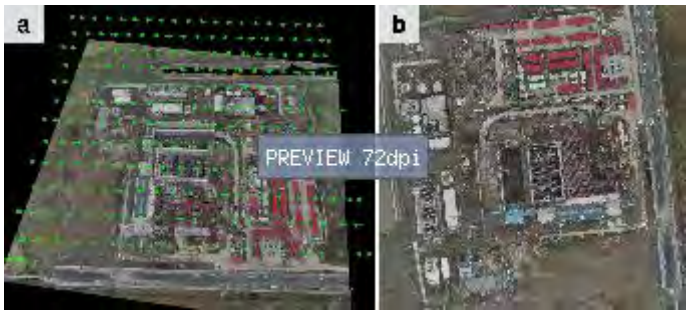


Figure 3. a) Flight route planning of the study area. b) The ortho mosaic image of the study area.

3.3. POST-PROCESSING OF UAV PHOTOGRAMMETRY AND 3D MODEL PRODUCTION

The post-processing made use of Pix4D Mapper (Vallet et al. 2011) to complete the oblique photogrammetry survey. In total, 2560 ortho and oblique images as well as POS data were input into the system to conduct image rectification. A relative difference between initial and optimized internal camera parameters of 2.63%

was acquired during the camera optimization process. The bundle adjustment of interior and exterior orientation was carried out with the mean re-projection error being only 0.2 pixels. With the use of dense image-matching technology, a Triangular Mesh Model (figure 4a) was acquired based on a dense point cloud of real images. Texture rendering was conducted on the triangular mesh model, and a 3D architecture model (figure 4b) was finally achieved.



Figure 4. a) The Triangular Mesh Model built for the study area. b) The reality-based 3-dimensional architecture model of the study area.

4. Automated Construction Progress Monitoring Using UAV-acquired Model and BIM-based Model

In this study, we used a specific structure (the chimney) in the construction site as an example to illustrate the applicability of our automated construction progress monitoring strategy. The chimney building is 70 meters high and approximately a triangular column design. Its BIM model (as-planned state) and UAV-acquired model (as-built state) are shown in figure 5. Particularly in the UAV-based model of the chimney, there is a whole set of scaffolding facilities along the column wall.

4.1. COMPARISON OF AS-BUILT AND AS-PLANNED STATE

During the construction period of our case study, there were always temporary structures, such as scaffolding components that are also reconstructed in the UAV-based point cloud. To split the scaffolding points in the model, we use a distance threshold because they are meters away from the wall structure model plane. In figure 6a, we see from the overhead view of the point cloud that real chimney structure points are significantly isolated from the scaffolding points. Using the method described by Tuttas et al. (2015) which is able to compare the photogrammetric point cloud with BIM model components, we obtain the result of the as-built and as-planned comparison. It should be noted that in order to clearly display the spatial overlap between UAV point cloud and BIM model, in the following figures, the point cloud is enlarged on the horizontal plane to a certain extent. Figure 6b shows that the dense point cloud acquired by UAV photogrammetry clearly indicates the already built components of the chimney. However, due to occlusions, the planes inside the exterior structures cannot be captured by the UAV cameras and are not represented in the point cloud, thus it cannot be determined whether they are built or not.

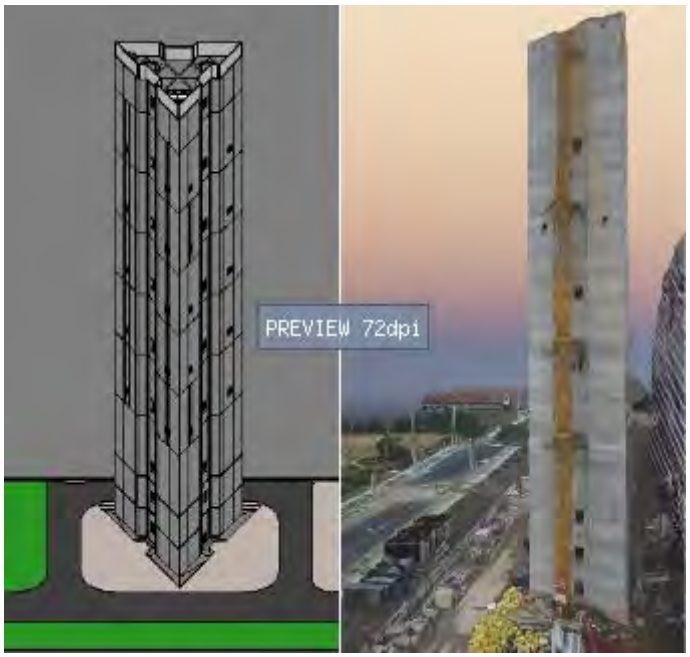


Figure 5. The BIM model and UAV-acquired model of the chimney.

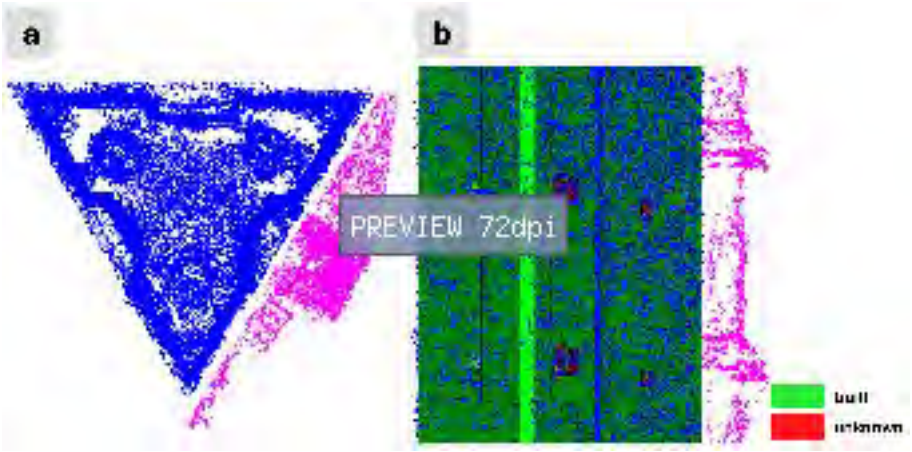


Figure 6. a) The overhead view of the point cloud. b) The comparison result of as-built and as-planned states. Blue points represent the points of real chimney structures, while magenta points represent the scaffolding components.

4.2. DYNAMIC CONSTRUCTION SITE MONITORING DURING TWO FLIGHTS

During the construction of our case study, we carried out two UAV flights in June and September. The comparisons of the as-planned and as-built state at two time

epochs are calculated below.From figure 7 a/b, it is clear that in June there are still scaffolding components around the top floor of the chimney. Figure 7 c/d shows that construction of the top floor in September is already completed. The scaffolds along the exterior wall have not been removed. We can see from figure 7d, which is the last flight of the construction site, that the exterior structure of the chimney architecture is completely built. However, the interior structure still needs a human to determine the status.

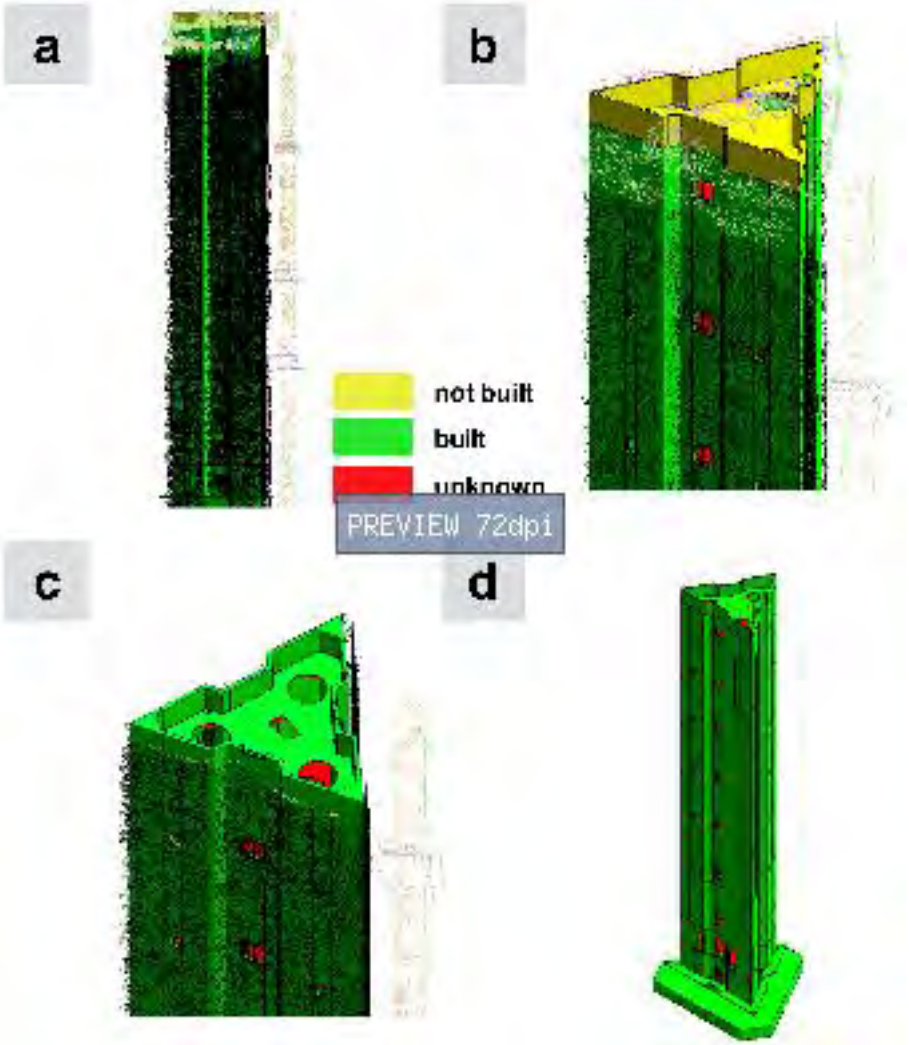


Figure 7. Results of as-planned and as-built comparison in June (a/b) and September (c/d). a) The whole chimney. b/c) Enlarged view of the chimney top. d) The final state of the chimney construction progress. Black points represent the UAV point cloud, while colorful points represent temporary structures such as scaffolding components.

5. Discussion and Future Work

This research applies low-altitude UAV oblique photogrammetry for quick and easy 3D modeling of the as-built process of construction programs. It demonstrates the capability, integrity, high precision and high efficiency of this process of architectural modeling. The BIM technology in conjunction with the use of UAV photogrammetry enables an as-planned and as-built comparison of construction progress. Hence, more effective project management and dynamic construction site monitoring can be achieved.

During the UAV-based 3D model production procedure, we found that defects do exist in the automated process. For example, the bump of the aircraft might lead to geometric distortion of images and result in a convex hull and holes in the generated model. Manual intervention, such as geometric repair and detailed decoration, might be needed in future optimization work. Our comparison strategy is currently fitted only for the given case study and needs to be tested on different cases to achieve a more robust validation for the future.

Acknowledgements

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APPLICATIONS OF INTEGRATED DIGITAL TECHNOLOGIES FOR SURVEYING TIBETAN ARCHITECTURAL HERITAGE:

Three Years of Experiences

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Abstract. Absence of reliable and accurate surveying of Tibetan architectural heritage has long been a major constraint for architects, architectural historians and archeologists working in that region. Due to distinctive geographical environment and architectural typology, unique surveying technologies are required in Tibet. In the last three years, integrated digital surveying technologies are applied to architectural heritage in Gyantse, a Tibetan city. The aim of the surveying is to document and analyze local architectural heritage for potential technical intervention such as consolidation, restoration and renovation. Key technical issues ranging from reliability of consumer-level UAV to BIM-based platform are presented in the article. The conclusions are that digital technologies greatly improve architectural heritage surveying in Tibet in terms of accuracy, efficiency and versatility. Future works will be addressed in more robust algorithms for points cloud semantic segmentation, change detection of large-scale architectural heritage based on remotely sensed imagery over time, and data exchange and coordination between BIM and GIS, etc.

Keywords. Architectural heritage; Digital survey; Tibet; UAV; BIM.

1. Background

The scientific study of Chinese architectural heritage dated from the pioneering work of Institute for Research in Chinese Architecture (IRCA) in the 1930s. Liang Sicheng and his colleagues discovered, surveyed and studied some of the earliest wooden architecture in the North China Plain. IRCA's research exerts tremendous influence on succedent researchers. Today, architectural historians still have strong passion on the same region and the same architectural typology. Advanced surveying technologies are employed to capture millimeter-level 3D data which arise new interpretations on Liang Sicheng's work. This is an evident case how architectural history research and heritage conservation benefit from the improved completeness and accuracy of surveying.

In sharp contrast to the wooden remains in North China Plain, absence of reliable metric data has long been the fact in Tibet (Wang 2004). Tibet takes up 1/8 of the country's 9.6 million square kilometers territory and it is the world's highest region with averaging altitude over 4000 metres. The shape grammar of Tibetan architecture is distinctive from the wooden structure in North China Plain. Multicultural influence from India and Nepal are reflected in Tibetan architecture. The architectural typology ranges from stupa filled with paintings and sculptures to castle on mountain top and ruins of vanished kingdom. Surveying Tibetan architectural heritage hence cannot simply copy the methods from North China Plain. Although TLS (Terrestrial laser scanning) enables automated and accurate 3D measurement, it is bulky, time-consuming, and has constraints in terms of scanning radius and angle. 2D drawings based on CAD software could represent manual measurement of single building, but it is not an ideal platform representing 3D surveying results and geographical environment. Integrated use of unique 'measured and drawn' technologies in Tibet is necessary.

Since 2014 IRCAHC (International Research Center of Architectural Heritage Centre) of Shanghai Jiao Tong University has been engaged in surveying architectural heritage in Gyantse, a city in southern Tibet. Gyantse was prosperous as the rise of Ancient Tea-Horse Road, a corridor linking China with South Asia since Tang Dynasty. The surveying is expected to document and analyze local architectural heritage with digital technologies for potential usages such as technical intervention. This article illustrates the workflow and discusses the metric results based on a set of case studies.

2. Digital Surveying Technologies of Architectural Heritage

When choosing the surveying technology for architectural heritage, the following issues should be considered: required accuracy, object dimensions, location constraints, the instrument's portability and usability, surface characteristics, working team experience, project budget and final goal of the survey (Remondino 2011). Optical measurement technology ensures automated and non-contact data acquisition with high accuracy. It is widely applied to surveying of large-scale and complex architectural heritage today (Rizzi et al. 2007). In the light of optical sensor types, optical measurement consists of range-based modeling and image-based modeling. Range-based modeling (e.g. laser scanning) employs active op-

tical sensor for 3D measurement directly. Having been commercialized for circa 20 years, the workflow from scanning to registration and meshing is quite straightforward today. Generally laser scanners are costly and bulky, while low cost and good portability are required in most cases. This is the major constraint hindering it from wider applications. The emerging wearable scanners and hand-held scanners are offering improved portability, flexibility and efficiency to data acquisition, but laser scanner fixed on tripod is still the most commonly type today given the factors such as scanning radius, cost and accuracy. Image-based modeling (e.g. photogrammetry and infrared thermology) uses passive optical sensor to detect light or thermal conditions of an object. Photogrammetry was applied to documenting architectural heritage even earlier than laser scanning. It recovers 3D measurement via image set photographed by calibrated camera and tie points registration among corresponding images. Conventionally both procedures, camera calibration and image orientation, require manual manipulation by skilled and experienced operators. Since a decade ago Structure from Motion (SfM) algorithms (Robertson et al. 2009) developed by computer vision community opened doors to non-expert users. SfM employs simultaneous camera calibration and image orientation, i.e.self-calibration (Pollefeys et al. 1999), to cater for automated applications. Even images photographed with different cameras, sizes and illumination conditions can be oriented via feature detection algorithms. A series open-source software (e.g. Bundler, Visual SfM, Apero) and commercial software (e.g. Agisoft PhotoScan, Pix 4D) are now available for image-based modeling. The booming of consumer-level UAV (unmanned aerial vehicle) in recent years makes low-altitude aerial image acquisition affordable and manageable to amateurs. The integration of SfM and UAV leads to promising applications such as surveying large-scale architectural heritage coupled with geographical environment. As image-based modeling relies on external reference such as Ground Control Points (GCPs) to correctly orient and scale the resulted 3D model, total station or GPS is mandatory when high metric accuracy is required. Manual survey is still useful in measuring small scale object with simple geometry such as room plan or component.

In spite of the strength of measurement technologies, the gap between data providers and data users is by no means bridged. In the light of data format, 2D drawing is still the preference of architects, architectural historians and engineers, while optical measurement outputs 3D results such as points cloud. Points cloud is a collection of huge amount points each defined by XYZ coordinates and RGB color. Although points cloud document architectural heritage with ideal accuracy and detail, the model itself is lack of semantic awareness, i.e. it is a frozen mass rejecting any modifications in common architectural software. The compromise solution is extracting a set of 2D contours from points cloud as footprints for 2D drawings. Apparently it does not take full advantage of 3D data and makes most of the on-field work redundant. Some research efforts have been put to the linkage of points cloud with BIM, e.g. HBIM (Historical BIM) (Dore et al. 2015) and as-built BIM (Barazzetti 2016). They leverage the power of BIM as a semantic-based platform with object-oriented parametric modeling. Once points cloud is transformed to BIM without the loss of geometric accuracy, further elaborations based on as-built state of architectural heritage are available such as structural analysis and

monitoring (Barazzetti et al. 2016). The current challenge is how to semantically segmenting points cloud into architectural components (e.g. column, wall, floor) with accuracy and automation. Although relevant algorithms exist (Ochmann et al. 2016), reliable and automated approach is still missed for architectural heritage given the complexity and irregularities of geometry.

3. Surveying Architectural Heritage in Gyantse

Stupas are Buddhism architecture widely spread in Tibet. As a symbolic presence of Budda, stupas are built like a cone with reduced floors upward. Such geometry causes occlusion problems for laser beams. All the terrace floors and most walls of stupa are beyond the coverage of TLS (figure 1). In contrast, UAV guarantees a much more complete coverage with low-altitude aerial images. These images could be employed to generate 3D models in SfM software.

3.1. ACCURACY OF UAV-SFM METHOD FOR 3D OBJECTS

The unsolved issue is whether consumer-level UAV is reliable in surveying a stupa. Although positive results have been reported recently on surveying 2D objects (e.g. land, building facade) based on UAV and SfM method (Ruggles et al. 2016), the issue is much more complicated in modeling 3D objects such as a stupa. Modeling the terraces and walls of a stupa literally leads to a convergent camera network composed by both nadir images and oblique images. The two images set have different camera lens orientation, image scale, and illumination condition. Feature detection and feature correspondence of such image sets are error-prone for SfM algorithms.

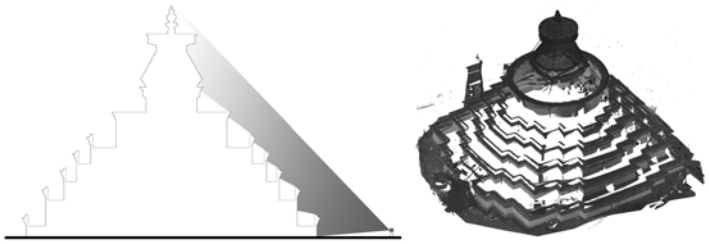


Figure 1. Limited coverage of TLS in surveying the Auspicious Multi-door Stupa.

The Auspicious Multi-door Stupa in Gyantse is one of the largest stupa in Tibet. It is located in Palcho Monastery which was established during AD 1418 to AD 1436 in Ming dynasty. Due to the occlusion problems using TLS, UAV-born images and GCPs measured with total station are employed for implementing image-based modeling. The employed UAV is DJI Phantom 4. The equipped camera has 12 million pixel resolution and 35mm lens (Table 1). As stated by the manufacturer, the chromatic aberration has been reduced by 56% and lens distortion had been reduced by 36% compared to Phantom 3 Pro. Both of the two factors are crucial to the quality of imaging and 3D modeling. The camera network is planned considering flight route, image coverage, lens orientation angle and GSD (Ground Sample Distance). In the end a camera network combining nadir images and oblique images with high image overlap is employed (figure 2).

Table 1. Table 1. Specifications of the employed UAV.

Specifications	
Weight	1380g
Flight time (max.)	28 min.
Sensor size	6.16mm×4.62mm
Resolution	4000 pixel×3000 pixel
FOV	94°
Focal length	35mm
Aperture	f/2.8

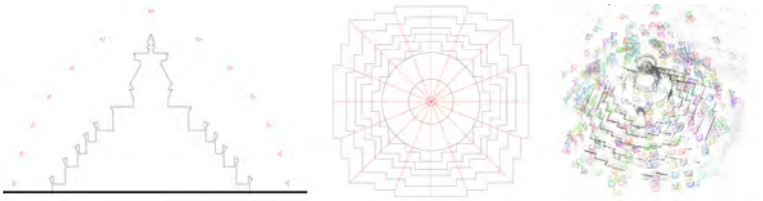


Figure 2. Employed camera network for image-based modeling.

A geodetic network is established with total station to evaluate the accuracy of image-based modeling. 55 evenly distributed GCPs (measuring accuracy: ±0.1mm) on each side of the Auspicious Multi-door Stupa (figure 3) are measured from 4 stations. The measurement targets are natural features (e.g. corners of painting) on the Stupa instead of commonly used print targets. The natural features are more durable and could be measured in the future for monitoring structural deformation.



Figure 3. Measurement and detection of GCPs.

The captured images are fed to commercial software Agisoft PhotoScan for automated 3D modeling. Measured targets are manually picked on the textured mesh, and local coordinates of GCPs are imported to the software to optimize the 3D reconstruction via bundle adjustment algorithms. The outputs include points cloud, texture mesh and DEM (Digital Elevation Model) (figure 4). The metric accuracy of the 3D model is also reported. It is the average accuracy reflecting the goodness-of-fit between GCPs and their corresponding locations on 3D models. The resulted RMSE is 2.05cm, 1/2000 the length (40m) of the Auspicious Multi-door Stupa. This accuracy is comparable to TLS given the potential inaccuracy of registering points cloud from many stations. More detailed evaluation is carried out by comparison with TLS-derived model (figure 5). Most points on UAV-derived model are in green indicating deviations to TLS-derived model are within ±1cm given the scalar field bar's range is ±4cm. The large planar surfaces such as walls tend to be more accurate than brackets and moldings. This is due to UAV-derived model fails to represent the sharp transitions at such parts of the stupa. Extracting vertical sections from the TLS-derived model and the UAV-derived model, it is observed that the sharp transitions on the first model are replaced by filleted corners on the second. The accuracy assessment shows the UAV-SfM method can be a low-cost substitution of TLS in Tibet with comparable accuracy and better portability, flexibility and on-field efficiency. The accurate and complete 3D model obtained with low cost and high efficiency provide great convenience than existing research based on TLS (Wang et al. 2012) to analysis purposes such as settlement analysis (figure 6).

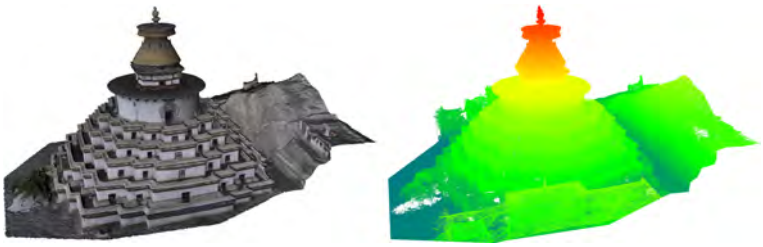


Figure 4. Outputs of image-based modeling.

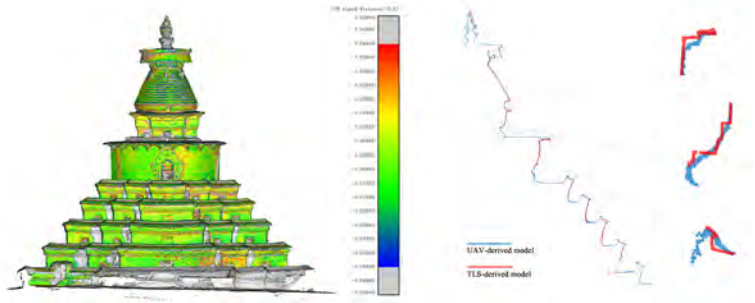


Figure 5. Discrepancy of UAV-derived model with GCPs as compared to TLS-derived model.

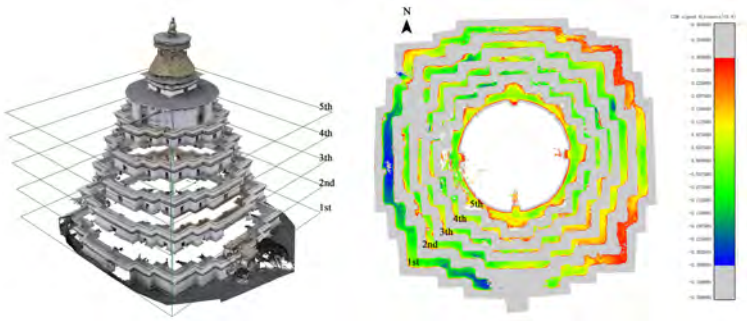


Figure 6. Surface settlements analysis of the stupa.

3.2. INTEGRATING VARIOUS SURVEYING RESULTS IN BIM

The old town of Gyantse covers circa 70,000 square meters. The main street of the old town links the Auspicious Multi-door Stupa and the Zongshan Castle, the two most important monuments of ancient Gyantse (figure 7). As one of the last untapped living heritages even in Tibet, the residences of old town are native herdsmen instead of operators of restaurants or shops. Measuring a town at such scale is beyond the capability of manual surveying, but digital technologies open doors for such demands.



Figure 7. Old town of Gyantse.

The surveying was carried out in the summer of 2015. Due to the large scale and complexity of the old town, integrated surveying technologies are employed. The 3D model of old town is generated by UAV-SfM method as presented in part 3.1. The determined GSD (Ground Sampling Distance) is 5.5 centimeters which is sufficient for surveying purpose and speeds up the on-field efficiency. A hand-held Canon 5D camera captures terrestrial images of the building façade along the main street for high-definition chromatic documentation. The points cloud generated from aerial images are aligned to the ground truth model derived by TLS (figure 8). The outputs of the surveying facilitate to mapping purposes (figure 9). The orthophotography of building facade along main street with high resolution and chromatic fidelity eases the intensive manual measurement for 2D elevation

drawing.

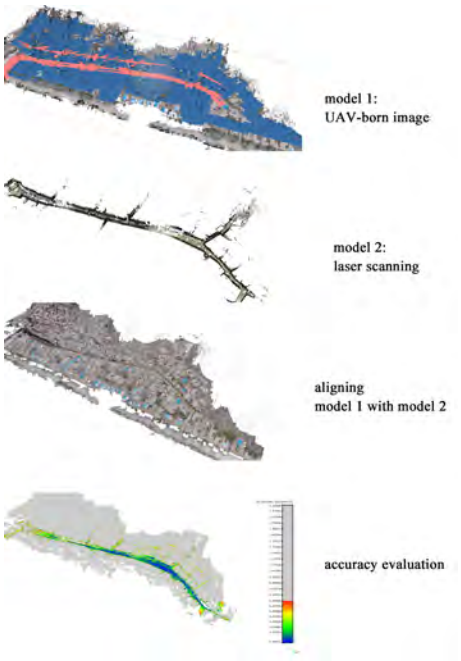


Figure 8. 3D modeling of old town with laser scanning and photogrammetry.



Figure 9. Surveying outputs of old town.

Some of the buildings in the old town possess valuable historical information. Luocuo is a 2-story building in the old town. As former Nepalese legation in Gyantse, a room of the building is full of elegant wall paintings. The main surveying purpose is collecting comprehensive data (e.g. geometry, color, invisible hollowings) for potential technical intervention. An indoor points cloud model of the entire building is obtained with TLS from several stations. Close-range photogrammetry is employed to document the chromatic information of the wall paintings. The output orthophotography reflects detailed metric data of wall cracks

and peeling off of pigments. An infrared thermal camera is employed to detect the hollowings beneath the surfaces which are crucial for disease analysis. The wide range of captured data requires a platform allowing multi-data management instead of conventional CAD-based drawing. A building information model is established in Revit, a commercial package of BIM (figure 10). As transforming the unstructured points cloud into parametric BIM model requires manual operation, a central issue of BIM development is distinguishing LoD (Level of Detail) according to the expected accuracy and scale. The advantages of representing surveying results in BIM consists of: 1) precise modeling based on tracing footprints of points cloud; 2) avoiding the common inconsistency among various drawings (plan, elevation, section); 3) providing access to further usages such as structural simulation.

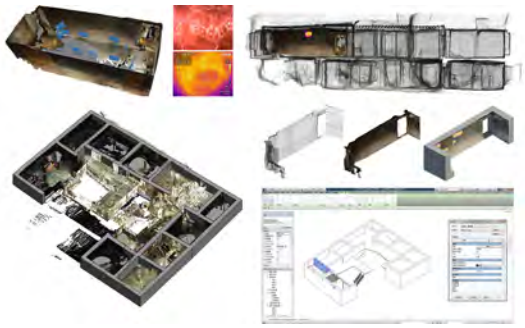


Figure 10. Integrating various surveying results of Luocuo in BIM.

4. Conclusions and Future Development

The digital surveying for Tibetan architectural heritage is an emergent task. The last three years surveying experiences in Gyantse witnessed the vulnerability of local architectural heritage. Some of the ancient remains collapsed due to natural reasons, but the largest threat is development and construction ignoring the value of cultural heritage.

The emerging digital technologies provide opportunities to better document Tibetan architectural heritage in terms of accuracy, automation and completeness. Instead of capturing merely geometric data manually or by TLS, the integrated usages of UAV-SfM method, close-range photogrammetry, and infrared thermology allows more comprehensive data acquisition ranging geometry to color and invisible conditions. Meanwhile, such methods are low-cost and portable which are crucial factors in Tibet. The UAV-SfM method is proved to be a reliable and low-cost substitution of TLS in certain situations with similar metric quality (relative error: 1/2000). BIM-based platform serves as a central database for managing comprehensive data, and bridge the gap between raw surveying results and further data analysis and simulation for architectural history research and technical intervention.

The unsolved issues during last 3 years are mainly how to efficiently fill the gap between ‘what was measured’ and ‘what to be drawn’. Although BIM is sup-

posed to be the most ideal platform currently for such demands, it is developed for AEC industry instead of architectural heritage. It leads to a time-consuming and tedious process from points cloud to semantic-aware models in BIM. In addition, CAD drawings are still necessary for fast and preliminary surveying. GIS-based platform is useful for managing large-scale architectural heritage. Consequently, a CAD-BIM-GIS coordinated database and drawing production method for various surveying purposes and architectural types are required in future work.

Other future progresses may be addressed in the following aspects: 1) new digital surveying technologies, such as panorama camera and relevant algorithms for 3D modeling wall paintings in grotto, multispectral imaging for diagnosing wall painting and producing remotely sensed imagery coupled with UAV; 2) change detection of large-scale architectural heritage based on remotely sensed imagery over time; 3) data exchange and coordination between BIM and GIS for managing architectural heritage in various scale.

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A PROPOSAL FOR BUILDING SAFETY DIAGNOSIS PROCESSES USING BIM-BASED REVERSE ENGINEERING TECHNOLOGY

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Abstract. Recently, the aging of buildings is accelerating around the world. In line with this, architectural structures constructed long time ago require life extension and ongoing management and protection for improvement, because they are too deteriorated. In particular, since structural safety inspection and analysis in building is very important, 'DFS (Design For Safety)'system has been introduced and conducted at the national level in Korea for the whole building life cycle management system encompassing the entire design, work commencement, construction, and completion stages. However, we do not have a system ranging from repair and reinforcement work plans in doing safety design, structural inspection and analysis to ongoing safety inspection. Therefore, it is necessary to establish a system to produce and share integrated information and conduct a research to manage architectural structure across the whole life cycle. Accordingly, this study aims to propose BIM-based reverse engineering technology for generating a safety management model based on laser scanner, verify the investigation items to be utilized of the design when building safety, and seek ways to utilize them for safety design.

Keywords. BIM; reverse engineering; building safety diagnosis; laser scanning; design for safety.

1. Introduction

Globally, the stocks of aging buildings are steadily increasing. Generally, the largest proportion of buildings are apartment houses. Compared to the life expectancy of apartments in developed countries, the life expectancy of Japan is about 54 years (2008), the US is about 71 years (2003), the Germany is about 121 years (2002), The average apartment replacement period is 54 ˜ 128 years (Park

2016). However, the average apartment replacement life in Korea is about 26 years (as of 2005). Although the minimum life span of a concrete building is 60 to 100 years, it is necessary to rebuild the apartment in Korea less than 30 years. In addition, not only in Korea but also in developed countries, the aging of the buildings is accelerating. The expansion, remodeling and reconstruction are frequently carried out, wasting costs and resources. Therefore, the structural safety of the building should be considered from the design stage, and structural safety diagnosis and analysis are necessary for maintenance (Park at al. 2016).

This study propose a laser scanner based BIM reverse engineering process for safety diagnosis model and improve the existing building safety diagnosis system by verifying the investigation items of safety diagnosis.

1.1. METHOD AND PROCEDURE

The procedure of this study is shown in figure 1. First, this study compared the present status of building safety diagnosis in Korea and abroad and analyzed the problems. Second, reverse engineering technology and laser scanner are reviewed. Third, the aged buildings requiring safety diagnosis were selected and processed with a laser scanner. Fourth, BIM-based reverse engineering was performed to generate the safety diagnosis model. Fifth, the survey items of the safety diagnosis were selected and the generated results were verified. Sixth, this study compared the process and investigation methods of the existing building safety diagnosis and laser scanner based BIM reverse engineering safety diagnosis. Therefore, this study proposed a process for new safety diagnosis investigation.

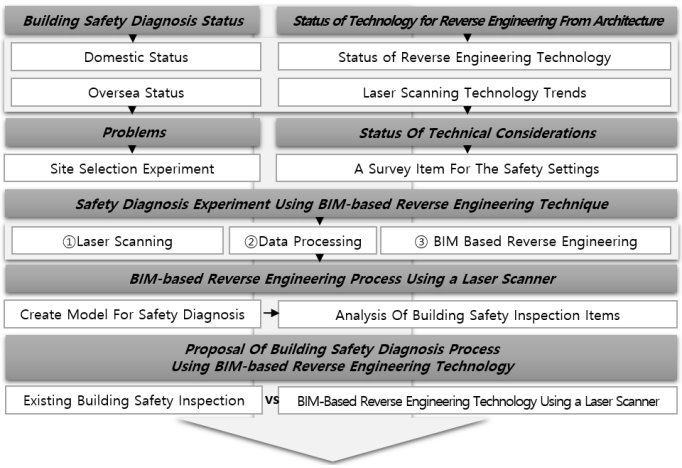


Figure 1. Flow chart of research.

2. Building Safety Diagnosis and Reverse Engineering Technology

Recently, advanced countries are discussing measures for maintenance and improvement of poor housing due to aging of buildings (Kim 2013). Especially

in advanced countries, DFS (Design for Safety) system has been introduced 20 years ago (Hee 2016). The purpose of the DFS is to transform the entire lifecycle safety management system of the construction industry, including the preliminary design, commencemen to work, construction, and completion phases. However, most safety diagnostics are conducted by private companies. This has limitations for visual inspection and examination. Subjective evaluation is carried out by checklist rather than objective safety inspection (Minstry of Land Infrastructure and Transport 2015).

Therefore, there are many problems in the results of safety diagnosis evaluation. Although the systematic efforts are being made to manage the safety diagnosis buildings, the safety check is practically carried out on the checklist rather than the practical inspection due to limitations of visual inspection, mixed computer systems, And the evaluation is dependent on them. Therefore, measures and techniques to improve the reliability of visual inspection are needed.

2.1. STATUS OF REVERSE ENGINEERING TECHNOLOGY AND LASER SCANNER

Reverse engineering is a technique for acquiring shape information using a digital device on a subject without design data and generating it as three-dimensional data. As a result of analyzing previous research related to domestic and overseas design, researches on data generation that extracts precise shape mainly using three-dimensional measurement data and reverse design method which accurately models from shape information are being conducted. In particular, current research is focused on automation of modeling such as complex MEP modeling and interior space shape extraction, and there is insufficient research on information utilization and process improvement based on point cloud including accurate location information (table 1).

Table 1. Reverse engineering related research.

Autho(Year)	Title
Jung, cho, & Whang (2008)	Automated Silhouette Extraction Method For Generating A Blueprint From 3D Scan Data Of Cultural Asset
Kwen et al. (2013)	A Fundamental Study On The Comparison Of As-Planned With As-Built Of Free-Form Building Skins Using Laser Scanning Technology
Lee & Kwon (2014)	A Study On Optimal Laser Scanning Method For Reverse Engineering At Interior Remodeling Project
Jung et al. (2014)	A More Practical Semi-Automatic Methodology For Improved Productivity Of As-Built BIM Creation With Respect To Large And Complex Indoor Environments
An(2015)	A Study On Description About Application Of 3D Scandata For The Survey Report Of Wooden Architectural Heritage
Hong et al. (2015)	3D Indoor Modeling Based On Terrestrial Laser Scanning
Chao & cho (2015)	A Study Automatic As-Is Simplified BIM Creation From Point Clouds For Energy Simulations

Despite the technology that can extract the current shape of the building, diagnosis and evaluation based on actual measurement are conducted in the case of the safety inspection of buildings such as old buildings, buildings without design data, and buildings without drawings (Minstry of Land Infrastructure and Transport 2011). This has led to many problems such as repeated loss of information in the actual measurement and recording process and lack of reliability in the evaluation of safety diagnosis. Therefore, it should be improved in the future for the accurate safety diagnosis investigation through the acquisition of objective data

and the process for efficient safety diagnosis evaluation.

Therefore, this study is different from the existing reverse design studies to accurately model the model from the shape information. This study propose a building safety diagnosis process that can be applied to the design by using the reverse design technology directly.

3. Building Safety Diagnosis Experiment Using BIM-based Reverse Engineering Technology

For the reverse engineering experiment using the laser scanner, the wooden structure was chosen as the experimental subject. Most concrete structures are many, but wooden structure are deformed and distorted due to their material properties. In addition, since the structure is formed by the bond between members, it is difficult to grasp the damage and corrosion of the joint part by visual inspection, so it is a structural type that needs continuous safety diagnosis. Therefore, if safety diagnosis can be done through BIM based reverse engineering using laser scanner, it can be easily reflected in safety diagnosis of other structures. In this study, the wooden structure type was judged to be valid and selected.

The site is located in Hae Yang Station (located in Hae Yang-eup, Gyeongsan-si, Gyeongsangbuk-do, Korea) and is now used as a warehouse. It is an aged wooden structure built in 1940 and is about 76 years old. The building is 23.9m in length, 8.6m in length, and 5.9m in height. The total area is 86m2. Details are shown in the table2.

Table 2. Building safety diagnosis target and experiment settings.

Site	1, Hayangyeokgil, Hayangeup, Gyeongsansi, Gyeongsangbukdo, Korea
Name Of The Building	(Former)Hayang Station The Platform
Building Structure	Timber Structure
ConStruction Year	1940Year
Square Measure	86.4㎡
Floors	Fault
Departments	Korea Railroad Corporation
Ect.	Railroad Cultural Properties Designation

The Scanning experiments were conducted with a tx5 device, a broadband scanner from Trimble, which is widely used at construction sites. Since the scan distance of this device is less than 10m (Trimble 2012). In order to extract the scan data of the target area, the photographing was performed 23 times in total, internal and external, and the shooting time was 135 minutes in total. In laser scanners, the point clouds decrease as the scan size increases with the resolution being equal, which lowers the precision. By contrast, when the scan size remains equal, the higher the resolution, the more the point clouds, which enables a precise measurement while increasing the data capacity (Trimble 2012a). Therefore, a high resolution (10.9MPts) and an average scan size (5120mm x 2134mn) were set for the experiment. Details of the scanner setting are summarized in table 3.

Table 3. Scanning device settings.

Device Name	Broadband Scanner In A Trimble Tx5
Range	Horizontal : 0 To 360° Vertical : -60 To 90°
Time	135Minute
Number Of Scans	23Inning
Resolution(Mpts)	10.9Mpts
Color	No
Scanning Spot	Inside & Outside
Scan Size(mm)	5120 X 2134

The evaluation items of the existing building safety diagnosis were analyzed for the experiment. Except for material test items requiring separate equipment and irradiation technology, nine visual inspection items were selected and tested (Minstry of Land Infrastructure and Transport 2011a). In order to verify the test items, test methods were set up by horizontal, vertical, height, depth, slope, thickness, number, and visual measurements. The details are summarized in table 4.

Table 4. Experimental setup items and BIM-based reverse engineering inspection method using the scan data.

Investigating Items	Contents Of Investigation	Method Of Inspection							
		Horizontal (mm)	Vertical (mm)	Height (mm)	Depth (mm)	Slope (°)	Thickness (mm)	Count (Unit)	Visually Research
① Standard	• A Dimensional Measurement Of Concrete, Steel, Masonry Walls	●	●	●			●		
② Displacement Transform	• The Slope Of The Building Four Sides • The Slope Of The Member Stress Survey					●			
③ Crack	• Cracking Width, Area Rate	●	●	●	●				
④ Surface Of Aging	• Damage Surface Of Aging Grasp								●
⑤ Joint Condition	• Weld Length, Angular Displacement • Number Of Bolts							●	●
⑥ Corrosion Degree	• Corrosion Degree Of Steel • Corrosion Degree Of Joint	●	●	●	●		●		●
⑦ Fire proofing Protection	• Fire proofing Protection Thickness, Damaged Area Of Member	●	●	●	●		●		
⑧ Member Stress	• Member Size, Section Dimensions Of Column, Beam, Bearing Wall Vertical Slab	●	●	●		●		●	
⑨ Structural Member Arrangement	• Structural Member Arrangement								●

4. Building Safety Diagnosis Process Using BIM-based Reverse Engineering Technology

In this study, the shape information of the building was extracted using TX5 scanner of Trimble. The extraction of shape information is carried out several times according to the size of the building. Accordingly, a process of merging into a single coordinate system is required, and a registration process is performed in which the merged data is placed on the relative coordinate system. Also, since the matched raw data contains a mixture of unnecessary data such as the surrounding terrain, trees, glass reflection, and noise, it is necessary to remove filtering data to leave only the data of the building. Realworks 9.1 program was used to post - process the scanned data of the extracted shape information and the capacity was optimized through the filtering process. In the experiment, the capacity of primitive data with only data matching was 4GB. After filtering, the capacity of data

was 1.58GB, which was reduced by about 60.5%. Figure 2 shows the raw data and the post-processed data.

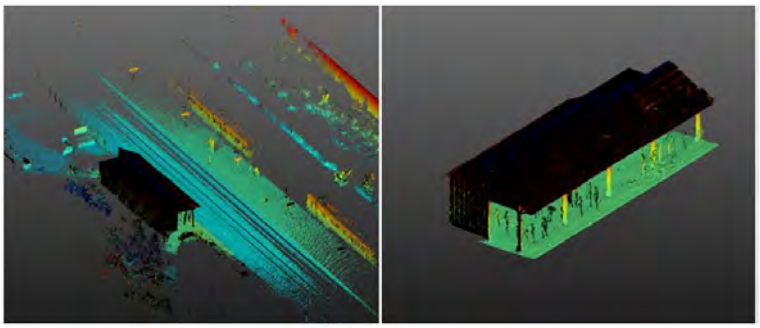


Figure 2. Raw data after data processing.

If converted to BIM-based file, repair and reinforcement can be planned through 3D modeling as well as investigation and measurement in safety diagnosis. In general, Revit (2017), a commonly used BIM program, transformed post-processed shape information (figure 3). The procedure for converting to BIM data is as follows. Point Cloud-based files were output via links in the Revit program. Therefore, the capacity of the point cloud after data post-processing was 1.58GB, and the capacity of data conversion based on BIM was 11.4MB, which was reduced by about 99.2%. Therefore, shape information was output through conversion of BIM-based data, and reverse engineering modeling was performed. Revit created the level and grid to match the linked shape information. Line Drawing was performed such as figure 4. Therefore, reverse engineering modeling enables recording, quantification and drawing. It is possible to construct reliable safety diagnosis data and to investigate and measure the evaluation items. This study proposes a building safety diagnosis process and verified the safety diagnosis items in section 4.2.



Figure 3. Import a 3D scan file into the BIM file.

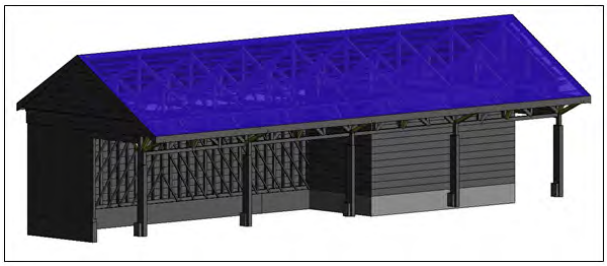


Figure 4. Shape of modeling based BIM.

4.1. ANALYSIS OF BUILDING SAFETY DIAGNOSIS ITEMS

(1) Measuring the member dimensions of concrete, steel and masonry walls

Generally, concrete, steel, and masonry walls have almost no irregularities on the surface. Therefore, the thickness of the wall is the same regardless of its position and height. However, the wooden structure has many irregularities on the surface. There was a difference according to position and height. Therefore, precise dimension measurement was possible according to the position and height of the member.

(2) Slope of the building and members

The Slope was investigated to analyze the displacement and deformation of buildings and members. The Slope of the building (horizontal displacement/building height) was measured based on the four exterior facades. The building was tilted by approximately 117 to the east. Also, the ground level was measured from the exterior scan data.

(3) Width and area of cracks

Since the wooden structure has many irregularities on the surface, it is impossible to measure the width and area of cracks. However, concrete floors have a smooth surface and almost no irregularities. Therefore, the detail of the cracked part can be extracted. This shows high utility in repair and reinforcement planning.

(4) Surface deterioration

The aging of the surface caused aging of the tree structure. The position, area, and progress can be grasped from the scan data, so that it can be visually recognized without a separate reverse design.

(5) Joining conditions (welding, bolt angle change and thickness)

The joining conditions is actually grasped by visual inspection. In this experiment, it is possible to grasp the position, type, number of bolts, and spacing of the joint by visual inspection from the extracted shape information without performing BIM-based reverse engineering.

(6) Corrosion of steel and joining

The degree of corrosion on the inner and outer surfaces of buildings can be grasped. However, it was impossible to measure the degree of corrosion of the joints of members. Since only the shape information is extracted from the scan

data, it is difficult to discriminate the corrosion of the joint with high precision.

(7) Estimating fire-proofing thickness and area of damaged members

Since a laser scanner scans only the shape of an object, it is difficult to identify the detailed components inside the wall. However, the accuracy of the point cloud differs depending on the type of member. Estimation of the approximate component of the member is possible, but not accurate. Therefore, it was impossible to measure the thickness of fire-proofing.

(8) Measurement of member size, section dimensions, load, deflection

Measurements of member size, section dimensions, loads, and deflection can be found in sections. The actual drawings were created with the shape information reflecting the state of the site as it is.

(9) Member arrangements and positions

The matched data can measure the placement and location of relative members. Also, 3D model was constructed from the shape information through BIM-based reverse engineering. The floor plan, elevation, section, structural diagram, and detailed diagram were extracted from the drawings.

Therefore, the results of analysis according to the items of appearance survey are as follows (figure 5).

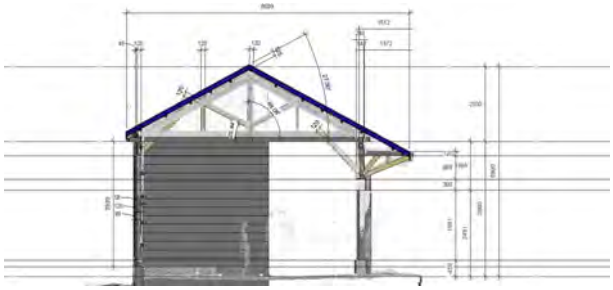


Figure 5. Analysis of Inspection Items for Building Safety Diagnosis using BIM-based Reverse Engineering.

As a result of the weighted analysis, 77.8% of the total 9 items of the survey items were improved (table 5).

Table 5. Whether Improvements of The Experimental Items and Weight Calculation.

No	Contents Of Investigation	Whether Improvements
1	• A Dimensional Measurement Of Concrete, Steel, Masonry Walls	O
2	• The Slope Of The Building Four Sides • The Slope Of The Member Stress Survey	O
3	• Cracking Width, Area Rate	△
4	• Damage Surface Of Aging Grasp	O
5	• Weld Length, Angular Displacement • Number Of Bolts	O
6	• Corrosion Degree Of Steel • Corrosion Degree Of Joint	X
7	• Fire proofing Protection Thickness, Damaged Area Of Member	△
8	• Member Size, Section Dimensions Of Column, Beam, Bearing Wall Vertical Slab	O
9	• Structural Member Arrangement	O

Note(Weight) : O Improvable(1), △ Some Improvement(0.5), X Not To Improve(0)

5. Conclusion

The existing building safety diagnosis has the following problems. The problem was identified by the subjective judgment of the inspector, the result of visual inspection, many field measurements, repetition of data input, time-consuming, and data format differences between drawings and reports. Therefore, this study proposed a building safety diagnosis process using the laser scanner based BIM reverse engineering technology. The conclusion of the study is as follows such as table 6.

Table 6. Existing Safety Diagnosis and BIM–based Reverse Engineering Technology Comparison.

Item	Existing Safety Inspection	BIM-based Reverse Engineering Safety Inspection
Measured Steps	During The Site Survey	After Post-Processing Data
Measured Period	A Number Of Site Survey	Once The Site Survey
Business Efficiency	The Site Survey ⇔ Repetitive Tasks Of Handwriting Input	Repetitive Tasks Will Not Occur
The Loss Of Information	Omission Of Information When Hand writing Input, Data Loss And Errors Occur	It Can Cause Errors In A Drawing Info rmation Extraction And Reverse Engine ering An Existing Drawing Information
Production Of Information	2D-based	3D-based
Drawings	Handwriting Input	BIM-based Reverse Engineering
Modeling	2D Drawing → 3D Modeling (Modeled After Creating Drawings Conduct)	BIM Drawing ⇔ 3D Modeling (The Modeling And Drawing Creation Performed Aut omatically At The Same Time)
Evaluators	1 Person	Numerous Experts Can Participate
Measuring Device	Ruler, Meters, Instruments , Etc.	Laser Scanner

First, the extraction of shape information based on the laser scanner solves the problem that depends on the subjective judgment of the inspector during visual inspection, so that anyone can obtain data that can be objectively investigated. In Section 4.2, one of the items that can not be surveyed was extracted from the extracted shape information among the nine items of appearance survey. As a result, 77.8% of the items were able to be improved by visual weighting. Therefore, objectivity is secured from extracted shape information.

Second, from the extracted shape information, BIM reverse engineering can generate 3D based safety diagnosis model and analysis by survey item. It is possible to measure, investigate, analyze, and plan future maintenance and reinforcement. As a result, repetitive work did not occur, and time reduction was improved. In particular, the analysis is performed according to the survey items in one scan, and the shape information is extracted without a separate handwriting input. It is possible to extract the drawing through the reverse engineering and it proved that the time reduction is improved.

Third, BIM-based reverse engineering can generate equivalent data for each survey item. It is efficient in making drawings and reports submitted in safety assessment evaluation. Therefore, it is possible to improve the problems of omission and non-entry of information in the existing safety diagnosis and to secure the adequacy of the results. Especially, if IFC extracts the data generated by BIM-based reverse design, it is possible to collaborate with many experts to improve the quality of building safety diagnosis.

Finally, the capacity of raw data is 4GB, but it can be lightened (62.5%) to 1.5GB by data post-processing. The BIM data capacity is 11.4MB, which is about 99.3% lower than the raw data. Therefore, the BIM-based reverse engineering technique can reduce the data capacity. This can contribute to the management of building safety diagnosis from the viewpoint of city. Furthermore, the connection of drones can contribute not only to safety but also to facility maintenance and urban disasters.

Therefore, this study proposed a process for building safety diagnosis by securing objectivity of data, shortening time, improving quality, and lightening data capacity. This can contribute to the maintenance of buildings in the future and can be utilized in repair and reinforcement planning. It is expected to contribute not only to evaluation of building safety diagnosis but also to technology convergence for construction automation of various fields.

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Big Data

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DATA MINING TOURISM PATTERNS

Call Detail Records as Complementary Tools for Urban Decision Making

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Abstract. In this study we show how Call Detail Record (CDR) can be used to better understand the travel patterns of visitors. We show how Origin-Destination (OD) Interactive Maps can provide transportation information through CDR. We then use aggregation of CDR to show the differences between the travel patterns of visitors from different countries and of different lengths of stay. We also show that visitors move differently during event periods and non-event periods, reflecting the importance of real-time data available by CDR. From CDR, we can gain more detailed and complete information about how tourists move compared to traditional surveys, which can be used to aid smarter transportation systems and urban resource planning.

Keywords. Machine Learning; Call Detail Record; Original-Destination Matrix; Urban Design Tool.

1. Introduction

The problems of congestion and resource allocation are essential to consider in urban planning and governance. These problems are becoming more severe as resources become more scarce. For a country like Andorra where the number of foreign visitors are high compared to the number of local residents, understanding the mobility patterns of tourists becomes important. Previously data collection related to tourism consisted of travel surveys completed from a sample of tourists. Travel surveys generally do not include locations in a tourist's path and are hence inadequate to fully represent the less regular and consistent travel paths of tourists.

Call Detail Record (CDR) is data from telephone calls collected by telephone service providers for billing purposes. CDRs are digital footprints of telephone

calls, including information of the time a call was made, and the corresponding cell tower used to process the call (Agung 2016). CDR can be used to more systematically and comprehensively track the movement and location of all tourists. However, the context of how CDR analysis can be applied to tourists is less explored compared to how CDR analysis can be applied to regular residents of a city. CDR analysis, as literature shows, can take advantage of machine learning, data visualization techniques to conduct more meaningful analysis, and in this paper we will use these methodologies in the context of tourism.

Following CDR analysis methodology used by Alex (Sandy) Pentland, at MIT Media Lab research group, we first created an aggregation map of tourist's CDR by time and nationality to understand population distributions throughout Andorra for different tourists events (Montjoye 2013). Then, the movement of tourists throughout Andorra for a single day was obtained via an OD Matrix and displayed. After understanding how tourists moved through the country, the Association Map was created with the association rule algorithm and the Random Forest algorithm over a year's worth of data to determine how connected cities were to one another for various months and holidays.

2. Literature Review

The utility of CDR in the context of urban data analysis is evident as the data is spatiotemporal. This non-conventional data source offers extensive information about human interaction that were not accessible to urban designers before. CDR is shown to be a good alternative to understanding mobility patterns compared to traditional methods of data collection like travel surveys for acquiring information of travel demand of cities, which are much more limited (Toole 2015) (Calabrese 2013). Much work has been done on how to apply CDR in the context of urban design (Jiang 2016) and transportation systems (White 2004). A mixture of machine learning, data mining, and data visualization techniques are used in literature to conduct meaningful analysis based on CDR.

Data visualization is a crucial tool to better communicate understandings derived from big data. This is demonstrated by Balduini et al., in their article "City-Sensing: Fusing City Data for Visual Storytelling" (2015), where researchers show how data visualizations can be used to make large amounts of information more accessible to humans while preserving the privacy of users through aggregation.

The use of origin-destination (OD) matrices to understand travel patterns through CDR is developed by Md. Shahadat Iqbal and his research team (2014). In 2015 these methodologies were applied and generalized to be applicable to different cities, serving as a unified guide to transportation demand modelling using OD matrices derived from CDR (Toole 2015).

However, many existing literature on CDR in the context of human mobility patterns are dependent on the regularity of the travel behavior of the callers, notably in situations where the locations of homes and workplaces are consistent and recurrent. The regularity and consistency in behaviour allows researchers to create predictive models of mobility patterns through behaviour modelling (Eagle 2009). In the article "A Hierarchical Approach for Identifying User Activity Patterns from

Mobile Phone Call Detail Records" (Khan 2015), the researchers use a hierarchical analytical model where CDR is increasingly filtered by daily mobility patterns to allow more detailed analysis of cellphone users in Bangladesh. The methodology of filtering this data, however, is dependent on consistency of an individual's daily travels (primarily between work and home).

3. Methodology

The empirical sections of this work are based on the CDR provided, in a anonymised way, by the Andorran Telecom Company and collected throughout a year. In figure 1, we can see an example of the original data frame.

	DS_CDNUMORIGEN	DT_CDDATAINICI	DT_CDDATAFI	NUM_DURADA	ID_CELLA_INI	ID_CELLA_FI	ID_CDOPERADORORIGEN
0	9aff9f9d53ebd77d2cc0edc6eddb761b0c1d5ae7166ea8...	2015.01.02 00:03:50	2015.01.02 00:03:50	0	2021	2021	20801
1	9aff9f9d53ebd77d2cc0edc6eddb761b0c1d5ae7166ea8...	2015.01.02 00:54:39	2015.01.02 00:54:39	0	2021	2021	20801
4	161e38db04f53740a00aaf1734d5b07a19381567261ebf...	2015.01.02 00:01:58	2015.01.02 00:01:58	0	19091	19091	20801
5	161e38db04f53740a00aaf1734d5b07a19381567261ebf...	2015.01.02 00:00:38	2015.01.02 00:00:38	0	19091	NaN	20801
11	a1497171f3fa9f67427840a9a2793445478f5dce51a717...	2015.01.02 01:24:00	2015.01.02 01:24:00	0	9162	9162	20801

Figure 1. Original Data Frame of CDR.

From the data we are able to classify tourists based on their country of residence from the code of their cell phone carrier. We are also able to obtain the location they were at when making a call from the start cell tower associated with the call. Using the ciphered phone number we are able to trace the path each caller travels based on the changing locations of their start cell tower.

3.1. ORIGIN-DESTINATION (OD) INTERACTIVE MAP:

Based on the CDR timestamps and geo-locations that we collected, we aggregated the data by tourists' initial cell towers' location and subsequent cell towers' location, in order to obtain the mobility paths of tourists. As an example, we found that at 10 am in the morning, the road from the border city of Pas de la Casa (neighboring with France) to Encamp (5 km to the capital) in direction to the Andorra La Vella, the Capital, experiences heavy movement congestion, while at 7 pm at night there is high movement congestion from Soldeu to Encamp (in direction to France), see figure 2.

Thus, this type of analysis allows us to find functional traffic problems throughout the country that vary in the day, allowing us to suggest to the government ways to implement new transportation system in specific areas of the country where improvement is needed the most, see figure 3.

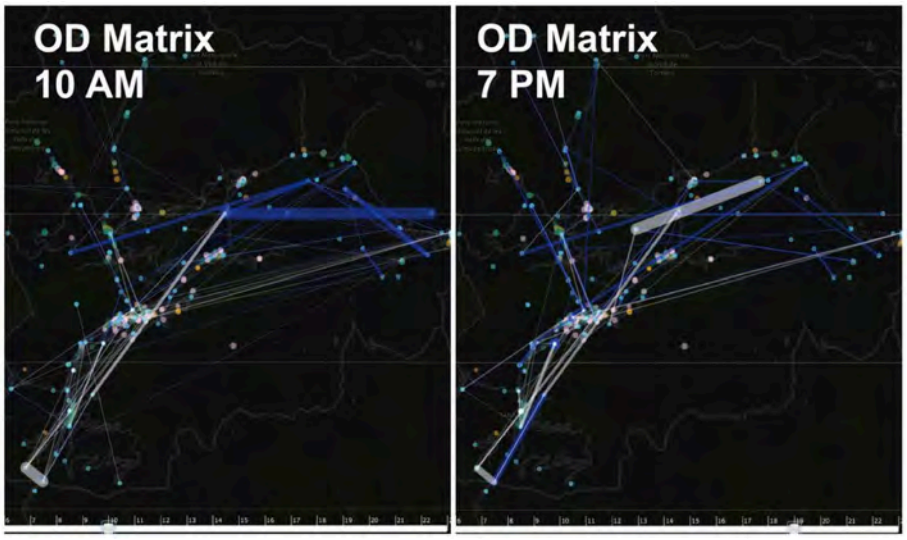


Figure 2. Origin-Destination Matrix showing changes in mobility pattern between morning and night-time, with white lines representing Spanish tourist movements and blue lines representing French tourist movements.

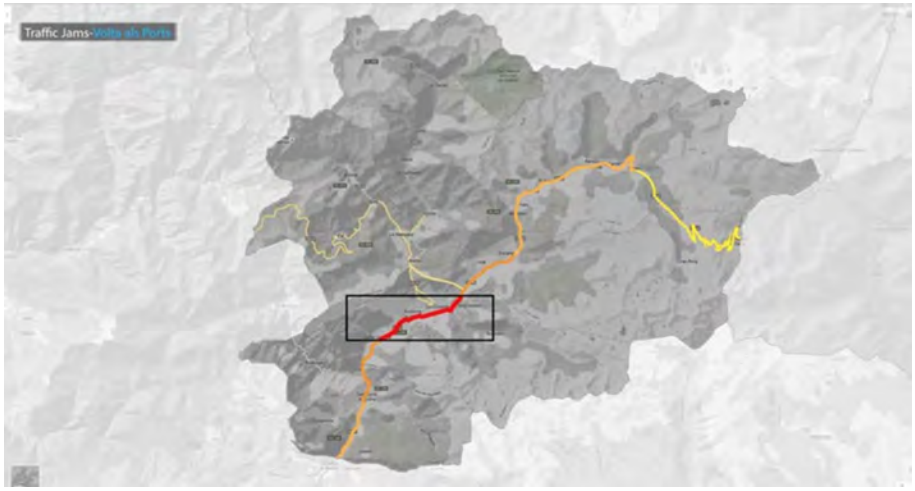


Figure 3. Traffic congestion on road segments.

4. Results

By connecting the locations of visitors as they make calls in different cities, we are able to aggregate the different paths of visitors to see which paths are most commonly taken by visitors of different countries. Our initial observations showed that tourists coming from the same country moved with remarkable consistency

within the same time of the year. Visitors from France and Spain make up to 82% of total visitors in Andorra. For French visitors the top 5 paths of travel between cities in July accounted for 54% of the total paths traveled by French visitors that month. For Spanish visitors the top 5 paths of travel between cities in July accounted for 62.7% of the total paths, see figure 4.

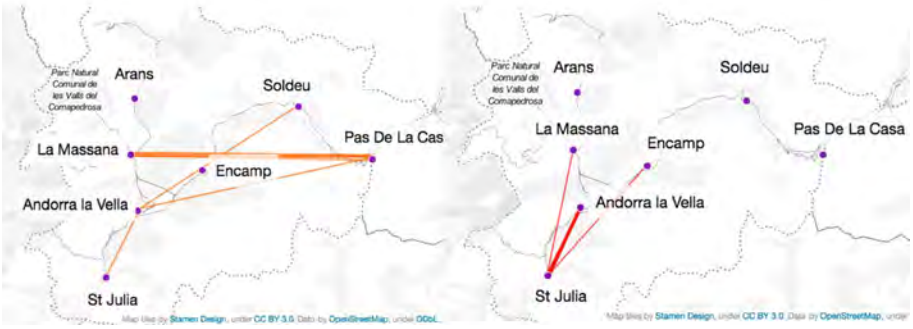


Figure 4. (Right) The orange lines and purple dots represent the top 15 paths traveled by French tourists in the summer. There is a mixture of dots and lines because some tourists only traveled within one city. (Left) The red lines and purple dots represent the top 15 paths traveled by Spanish tourists in the summer.

In the case of tourists in Andorra, one would think that the popularity of paths are highly dependent on proximity to country of residence because there are no airports or rail stations in Andorra, and hence most visitors are travelling by car or bus. To support this, we can see that the most popular path for Spanish visitors is St Julia, the westmost major city (closest to Spain), and and the most popular path for French Visitors is Pas De La Casa, the eastmost major city (closest to France).

A closer observation shows that this does not cover the full story. From figure 4 we can see that though the paths of visitors from different countries are quite different, both St Julia and Centre made the top 5 for both countries, suggesting that they are major touristic cities despite proximity. In addition to that, La Massana, a city by proximity closer to Spain than to France, is much more popular for French tourists. This suggests that the popularity of cities are dependent not only on proximity but also other factors. Road transportation connectivity may be part of the reason.

We then look at the top 15 paths taken by French and Spanish visitors, see figure 4. The same seven cities made it into the top 15 paths travelled by both Spanish and French visitors, reflecting that these seven cities are likely to be the major cities for tourists in Andorra. Aside from that we can see that French visitors are more likely to move around the country, whereas Spanish visitors are more likely to stay in the west of the country.

Thus, this type of analysis allows us to find functional traffic problems the country, and allows us to suggest to the government implementation of new transportation systems in specific areas of the country that need it the most.

4.1. COMPARING VISITORS DURING EVENT PERIODS AND NON-EVENT PERIODS

Through our CDR we were also able to see how visitors during event periods traveled around the country compared to non-event periods. Tour de France is one of the biggest events in Andorra in the month of July, running for multiple days and bringing a noticeable increase of visitors.

In figure 5, we can see how Tour de France changed the paths of the visitors not from either France or Spain. We see how movement to and from St Julia becomes more common during Tour de France compared to July in general. At the same time, movement to and from Pas De La Casa becomes less common during Tour de la France compared to July in general. With this example, we learn that events can change how visitors move. This strengthens our argument that real-time information is important to understanding the transportation needs at a point in time.



Figure 5. (Left)Top 15 paths travelled by visitors not from France or Spain during July.(Right) Top 15 paths travelled by visitors not from France or Spain during the period of Tour de La France.

5. Discussion

The present study provides evidence that the aggregation of CDR with other geolocated data can help the researchers to understand the patterns of different tourists that visit Andorra. After a validation and calibration of the methodology through a comparison with the surveys from Andorra Tourism, a series of interactive maps have been done to analyze and visualize the overlap of aggregated data, and to serve as a base for simulation-prediction tools like the Origin-Destination prediction tool presented in this paper. The simulation-prediction tools are designed as a decision making supporting tool [decision support system (DSS)] in the urban and territorial planning level.

As an example of our finds we can study the behavior of French and Spanish tourists. In figure 6 we can see that most of the Spanish tourists (the 40%) stay in Andorra La Vella (the Capital), which means that the Spanish tourists are focused on shopping and cultural events. The next likely movement is to go back to Spain (42% have St. Julia as a second step of their movement), though some of them continue to visit locations related to nature (more than the 14% have as a second movement cities related to nature and sports), which means that incentives and

new tourist and mobility policies could incentive Spanish tourists to visit other cities in the country as well, see figure 6.

On the other hand, if we focus on the flow of French tourists, we can realize that they are mostly interested in shopping (84% of French tourists in Andorra stay in Pas de la Casa, a very commercial city), and the next natural movement is to return home. Around the 16% of the French tourists have as second destination cities related to nature and sports, so once again, as with the Spaniards, this means that some incentives and new tourist and mobility policies can incentive them to visit other cities in the country, see figure 6.



Figure 6. (Left)Next City Prediction in French Tourists. (Right) Next City Prediction in Spaniard Tourists.

5.1. URBAN DESIGN IMPLICATIONS

From all that we already have shown, we can conclude that the country of Andorra experiences a profound and focalized change of population during tourist events. This puts a large strain on resource allocation in the country. Resource allocation is a general problem in the 21st century world, owing to resource scarcity (Glenn and Warner 2016; Semertzidis 2015). In general, within cities, a significant amount of resource and energy waste stems from the rigid and centralized methods by which urban centers distribute resources. Schedules for distribution are typically static over time, blind to mismatch between supply and demand of resources, generating waste.

The use of linear regression models based on CDR data in order to predict district activity density is growing as a compelling methodology that promises to have great impact on the urban planning design. Our method of combining CDR and Open Data to inform the deployment of new mobility systems is aligned to this innovative methodology, and focuses on the optimization of the overall large-scale mobility networks. Figure 7 defines the path used by the method in order to achieve the mobility demand forecast.

The first urban design implication is that a well-stocked data gathering where a correlation between CDRs, social activities and environmental factors can easily be made is key in order to study, understand, and design a mobility system.

The second urban design implication is that in order to analyse and simulate a mobility demand system (what we call, in figure 7, the “Demand Pattern”), an iterative process of refinement is needed. This iterative process is divided into three steps:

1. Aggregate demand pattern: Based on a "real-time" origin-Destination (OD) Matrix, the pattern correlates the social and environmental influences (or impacts), so a compelling mobility behavior can be defined.

2. Decision Support for Mobility Planning: A mobility on-demand toolset is proposed as a design solution. A combination of on-demand/shared vehicles, transit service frequency adjustments, multi-modal planning and transit hub planning is modeled depending on the needs of the stakeholders, the aggregate demand pattern, and other mobility inputs.

3. Deployment simulation: Before a complex demand forecast simulation is deployed, a real-time traffic simulation (that it can be based on Google Traffic real-time data base) is recommended, so a fleet size sensitivity test can be conducted.

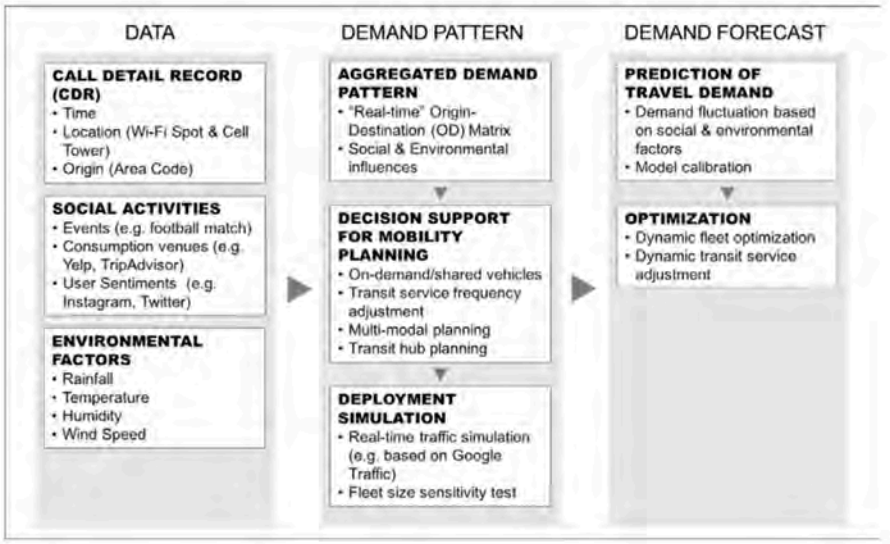


Figure 7. Method of combining CDR and Open Data to inform the deployment of new mobility systems, adjustment of existing transit services, and optimization of the overall network.

The last implication is that for defining the scale of the mobility system, a demand forecast is required. This last phase of design is focused on the calibration of the model based on the demand fluctuation dependent on social and environmental factors. As a final step of the method, the optimization of the model will bring the final numbers for the dynamic fleet optimization and the dynamic transit service adjustment.

Finally, from all that we have shown, we can conclude that the country of Andorra experiences a change in travel patterns during tourist events. This puts a large strain on resource allocation in the country, so a new mobility system based on our method is needed. In fact, resource allocation is a general problem in the 21st century world, owing to resource scarcity. Schedules for distribution are typically static over time, blind to mismatch between supply and demand of resources, and so, generates waste.

Andorra has an average volume of approximately 200,000 tourist per day, while the local population of Andorra is approximately 70,000. So a better understanding of the tourists (urban/country "users") can help the territorial and urban decision making, spread resources in the economic ecosystem, and balance environmental impacts. A dynamical scheduling system can be suggested to solve this problem and also encourage tourists to explore more deeply the country, balancing the tourist's environmental impact, spreading the tourist's economic impact. We conceive that a dynamical system, updating resource allocation based on real time localized demand, is able to actively update areas of supply and demand mismatch in real time, and is thus able to optimize resource management at all times.

6. Conclusions and Further Research

In this project, we explored whether we could learn about the travel patterns of tourists in Andorra through CDR. Through this analysis, we were able to identify that by far the two largest groups of tourists in Andorra were from France and Spain. We were then able to identify different types of tourist travel plans among tourists of different countries of residence. The most popular paths for Spanish and French visitors and tourist is traveling to St Julia (Spanish 32.2%) or Pas De La Casa (French 25.6%). This pattern changes during the events, such as Tour de France.

In the future, we wish to explore this further. In collaboration with the Andorran Government and their institutions, we plan to evaluate the use of social media and CDR data to infer resource demands by testing three uses in three major urban planning resource problems:

a) how to optimally distribute public transportation services and dynamically allocate vehicles.

b) how to optimally distribute emergency services in event of man-made or natural disruptions.

c) how to optimally distribute utilities (e.g. electricity) to prevent overloading the grid.

The final goal of this research is to find the elements that will allow us to design a high-performance, livable, entrepreneurial city.

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URBAN AUTOPOIESIS

Towards Adaptive Future Cities

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Abstract. A city, defined as a unity of inhabitants with their environment and showing self-creating and self-maintaining properties, can be considered as an autopoietic system if we take into account its bottom-up processes with unpredictable behaviour of its components. Such a property can lead to self-creation of urban patterns. These processes are studied in well-known vernacular architectures and informal settlements around the world and they are able to adapt according to various conditions and forces. The main research objective is to establish a computational design-modelling framework for modelling autopoietic intricate characteristics of a city based on an adaptability, self-maintenance and self-generation of urban patterns with adequate visual representation.The paper introduces a modelling methodology that allows to combine planning tasks with inhabitants' interaction and data sources by using an interchange framework to model more complex urban dynamics. The research yields preliminary results tested in a simulation model of a redevelopment of Tanjong Pagar Waterfront, the container terminal in the city of Singapore being transformed into a new future centre as a conducted case study.

Keywords. Urban Metabolism; Urban Autopoiesis; Computational Interchange; Emergent Urban Strategies; Adaptive City.

1. Introduction

The research explores aspects of self-maintenance, adaptability and self-creation of urban patterns transformed into a domain of interacting urban community of inhabitants represented by urban agents together with its physical urban structure.

1.1. BACKGROUND AND RESEARCH QUESTIONS

In this particular research study, the concept of autopoiesis covers the way how the urban structure is created, transformed, distributed or redistributed, assembled, organised, reconfigured and proceeded. This implementation of the autopoiesis paradigm into urban systems aims to grasp more complex characteristics of the city within the contemporary urban design discourse, in particular, tendencies of patterns to grow or decay according to inhabitants' requirements, distribution flows of energy, costs, goods, services or city networks connectivity (virtual, physical or social) related to an entire urban metabolism.

In a long term perspective this investigation tries to identify and discuss internal dynamics in a selected part of the city of Singapore that can help experts to better position their decisions. In so doing, several research questions need to be addressed: Which kind of urban forms and systems are more convenient in terms of rapid changes (social, behavioural, spatial) in our contemporary cities? Which urban tectonics and morphologies are able to efficiently react to various forces in cities, such as population growth? What kind of urban activities are able to maintain themselves according to local and external interactions and relay of information? Is there a convenient way of visual understanding of unpredictable processes and unexpected features of our future cities that can inform experts?

Although the research questions relate to broader aspects of urban environments, the notion of the autopoiesis presented here is focused on significant properties of an urban system which actuate the urban patterns to grow and subsequently lead to new conditions of urban configurations that urban growth refers to. In particular, it covers internal spatial relations between particular interacting urban units (agents in relations with an urban mass) that make the system constantly self-referencing (Maturama & Varela 1980) and in a state of dynamic self-creation. The urban environment investigated in this research study is reduced in its complexity with respect to its spatial aspects (Luhmann 1975; 1982).

1.2. PROBLEM STATEMENT

Following these features of autopoiesis mentioned above, urban designers still facing the problem how to model and simulate various complex characteristics of urban environments in one robust and comprehensive simulation and at the same time. Moreover, these characteristics and dynamics are dependent on themselves and they are creating never ending intricate processes of continuous transformation, which makes a city environment *always in a state of flux, growing and decaying* (Verebes 2014).

Other aspect of the problem outlined here is the designer's intention and his contribution to an urban layout generation. To simplify the entire design process, it is necessary to proceed his or her design intervention into the modelling framework as interactively as possible and minimize the computational process within an entire system. More specifically, the designer would be able to manipulate with the system in an intuitive way.

1.3. RESEARCH OBJECTIVES

The paper aims to establish a modelling workflow which reflects the above mentioned facts and would allow urban designers and experts to deal with various sources of data, e.g. external big data sets, user interaction inputs from a different application in order to obtain one robust modelling environment incorporating more complex urban phenomena and dynamics. Thus, the main research objective in this particular research study is to provide a framework, a simulation platform for architects and urban designers which will combine designer's top-down design requirements and bottom-up inhabitants' community demands and their interactions into one system as a modelling application with an interactive visualisation.

1.4. SCOPE OF THE PAPER

The paper introduces a modelling methodology approach based on a connection of two different applications for urban designers interacting between themselves (Rhino/Grasshopper and Java/Processing agent-based model) and combined with the user's input and interaction in a real-time process. To test the performance and interactivity features of modelling more complex urban design scenario, we propose a custom-oriented computation interchange framework, namely the LUCI (Treyer 2016a). In particular, the Tanjong Pagar Waterfront in Singapore has been selected as a test site for the experiment. The modelling approach involves selected bottom-up spatial demands, such as accessibility distances defined by the user in the graphical interface, spacing distances between urban elements and equable spread of urban functions in order to obtain mixed-used urban environment.

As a resulting outcome of this research, the study provides several spatial scenarios with variants, for urban designers' consideration. These are introduced and explained in section 4. The paper does not provide final designs and overall modelling of all metabolic urban layers, such as its mobility, transformation capacity, energy and waste flows, however it outlines a base for a modelling framework, where these aspects can be incorporated later on from other applications via the interchange platform LUCI.

2. State-of-the-art Review

As Christine Boyer states (2015), a city, an autonomous entity expressed in a living metabolism, *is adaptable to many forces and dynamics.* The phenomena of an emergence in the framework of cities as complex systems are known from theories as from Michael Batty's work (2014) modelled by means of cellular automata and agent-based models or concepts of cities as metabolic networks, e.g. theory of "Netzstadt" (Baccini 2014). According to Varela (1979), the autopoietic system is structurally linked to its environment, adapts according to its local or external conditions and maintains its internal organisation within this environment. It is a *complex organisation in which information transmittal, reception and interruption proceed recursively through continual feedback and feed forward across multiple levels within the system* (Boyer 2015).

According to Spyropoulos (2013), it is necessary to understand today's contemporary context where architecture must be engaged with the *information-rich*

environments and continuously changing demands for *adaptive models for living*. His approach, as he claims, explores possibilities where *the interplay of local agency and environmental stimulus constructs collective order[...], governed through emerging collective interaction.*

To model such complex phenomena of a city, it is necessary to take into account mutual dependencies of particular urban aspects together with urban designer's intention which communicate between each other and exchange information. The conventional modelling applications do not provide communication functionalities related to multi-layered interwoven processes dependent of themselves. The advantage of our proposed communication interchange platform, apart from other communication platforms, e.g. gHowl components (Fraguada 2016) or Functional Mock-up Interface FMI (Junghanns 2016), is that it is capable to incorporate various urban data sources or connections with other interfaces or applications developed in different programming languages or models in different scales and different platforms in one more robust system. The workflow is not time-consuming and not demanding a higher computational power, offering an open source environment for other contributing developers (Treyer 2016b).

The simulation of urban growth with agents is done also in popular games like Sim City (Wright 2016 [1989]) or rule-set-based urban growth platform City Engine (Esri 2016). Although the game Sim City is not related to any urban design tasks, it can serve as a valuable information source how the urban growth rules are incorporated within the entire system. Therefore, an urban design modelling process with the game-like graphical user interface can be as similar as playing a game in an intuitive way.

3. Methodology

The proposed Lightweight Urban Computational Interchange system LUCI (Klein & Treyer 2016) serves as a communication and management distribution channel between modelled urban metabolic layers in general, and dynamic data sent from different modelling interfaces (e.g. Rhino/Grasshopper) represented by the designer's predefined urban patterns, later distributed into a dynamic generative model (figure 1).

3.1. LUCI - LIGHTWEIGHT URBAN COMPUTATION INTERCHANGE

More specifically, this paper investigates an urban growth based on an accessibility and spacing distances between particular urban elements. An imported data set is subsequently read by the agent-based generative simulation model and displayed as a simplified 3D environment. This particular layer, in this case the external geometrical data set from the Rhino CAD application, is transferred into a computational service within the LUCI interchange system and involving the designer's parametric geometrical modifications in Grasshopper each time it is modified or changed. As such, the modifications are read and sent by the LUCI and the simulation is fed in a real-time process.



Figure 1. A designer's modelling framework containing a library of various predefined shapes transferred into an ABM simulation for a subsequent interaction with agents. The data are exchanged by the LUCI middleware. .

Rhino/Grasshopper is well known for serving as a integration platform for various applications within the realm of digital architectural production. It is possible to connect Rhino/Grasshopper through gHowl to a number of compatible applications through TCP and UDP networking protocols (Fraguada 2016). Yet, Rhino users ever again hit limits. Grasshopper is known for being rather slow, not able to handle enough geometry to be suitable for large urban planning and it is single-user centric. There are some startups, such as Flux or Shape Diver (2016), that aim to provide solutions to overcome this by bridging Rhino/GH to the Internet, to Excel, to Autodesk Revit. Still, these solutions focus on Rhino and heavily depend on Windows as their main platform. With LUCI we follow a slightly different approach. The aim is to provide a neutral, open source platform and programming language independent framework. It has a modular structure that allows interested developers to replace modules in case they favour to.

As a result, it will bring a comprehensive simulation and generative model depending on a real-time user's modification or other external data source that can be embedded, such as a vector position for various urban features, any quantified definition of many variables or pre-defined shapes of urban patterns for each of the used urban typology, in this case housing, public buildings or open public spaces.

3.2. ABM SIMULATION MODEL

The core of the generative simulation model introduced here is based on the EmCity platform (i.e. *Emergent City*), an agent-based simulation developed in previous phase of the research (Buš 2015). The agents try to achieve their demanded target (private or public building or a space) in a specific predefined accessible distance. If it is not achieved, the required urban unit or an activity appears, adapted to current distance requirements.

The model has been adapted to Tanjong Pagar site for this particular case study purpose and enhanced with interactivity features, where the user is allowed to mod-

ify the initial positions of agents in regard his or her preferences in the graphical user interface. As such, the observer controls the positions where agents are released from, in an interactive way and in a real-time process. Moreover, each initial position has been weighted with an user-defined number of released agents. In that manner the user specifies the level of importance for each particular initial position which reflects the real scenario more properly. The source code of the EmCity model is available as an open source platform under the GNU General public licence (Buš & Kurilla 2016; Treyer 2016a). The CAD data source regarding the Tanjong Pagar site as an initial geometrical input has been transferred into the model from the Open Street Map platform.

3.3. MODELLING PROCEDURE IN A CASE STUDY

In this section we aim at demonstrating LUCI's potential by showing how it can be used to interlink different applications on different machines with different operating systems. With this setup we want to provide multiple comparative views of the case study area. The principle step is the creation of urban geometry based on an agent simulation, which incrementally adds buildings to a scene corresponding to the behaviour of its agents that represent inhabitants in a simplified way. With every iteration the attached views will be updated. All views not only synchronise their geometry but also the camera angle at which the geometry is presented.

The geometry creation is implemented in a Java-based Processing Application. The typologies that are being placed in the scenario can be modified real-time in Rhino. The comparative views are provided by a Java application that uses OpenGL for display. Additional views are provided by Blender for ray-trace rendering as well as by a web viewer that theoretically allows to present views to any connected participant in the internet.

4. Generation of Urban Patterns in Tanjong Pagar Waterfront

The modelling and simulation framework has been set by connecting Rhinoceros/-Grasshopper designer's interface and the Java-based agent simulation model EmCity by means of the LUCI middleware platform.

4.1. RESULTS AND OBSERVATION

The user is allowed to observe growth of the urban area based on the designer's predefined spatial scenarios of various types of shapes and configurations (figure 2). Data are sent to the LUCI in real-time and displayed in the viewer. The geometry can be modified by the designer and it is updated in the display window. By using this methodology, the bottom-up growth of the city is simulated according to criteria of accessibility, spacing distances (density), spread of urban typologies and positions of agents and different spatial scenarios are built, visualised and stored. The LUCI stores and proceeds the data for further observation or rendering using other applications, such as Blender in a real-time process.

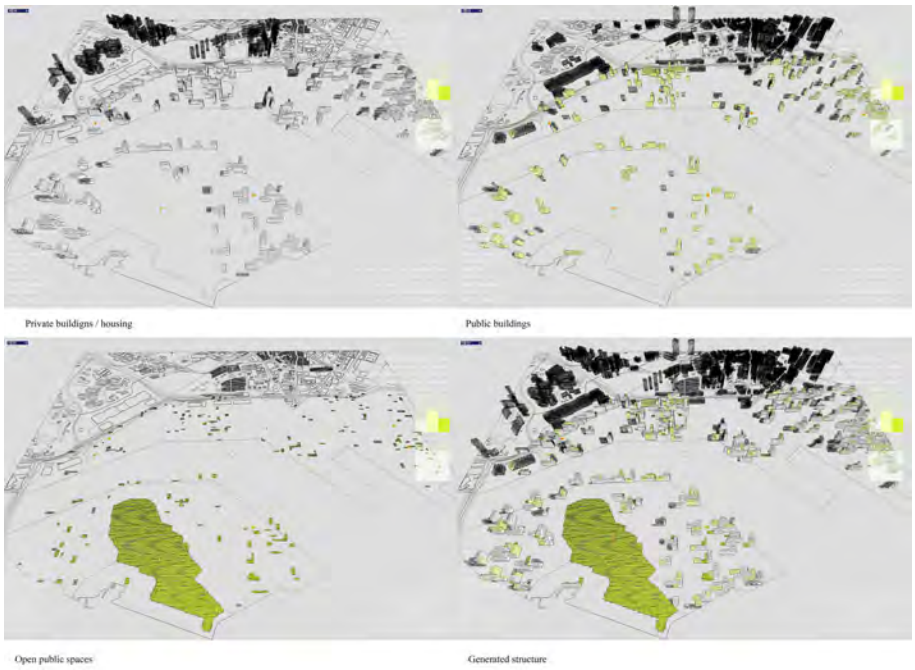


Figure 2. Combination of user-defined typologies in one urban layout. Different types have been sent from Rhino to the ABM model during the simulation process.

Thus, the framework allows to connect modelling software, rendering application, Java-based agent simulation and several display windows with the same or different camera positions, if necessary. In that manner, architects are able to gain and deal with big urban scenarios efficiently and from different perspectives, incorporating more complex and behavioural urban phenomena into a design process, displaying various aspects of the urban scenario at the same time.

The urban patterns, as it is observed from the agent-based simulation, grow and adapt according the user's preferences in terms of specification of agent's interactions, their initial positions and locations with weights combining with the formation process based on the designer's definition of the spatial scenario. A combination of bottom-up autopoietic growth together with the user inputs will allow to model more complex urban features considering the intuition of the designer. This cognitive approach of design computing, involving human's interaction with the machine, can yield more appropriate design scenarios related to real demands and bottom-up requirements, but still taking into account the designer's inputs and contribution.

The volumes of urban mass are generated in the ABM model. They are located according to random positions following the locations of agents themselves, their spacing distances and the accessible distances to particular buildings. The growth of the new added volumes proceeds based on demanding accessible distance set by the designer in the graphical user interface. The heights of the buildings can

vary in accordance with the user's parameter inputs in Rhino. Each input yields different results. Although the character of the layout is comparable and similar for each investigated scenario (figure 3), the outcomes are always different (figure 4).

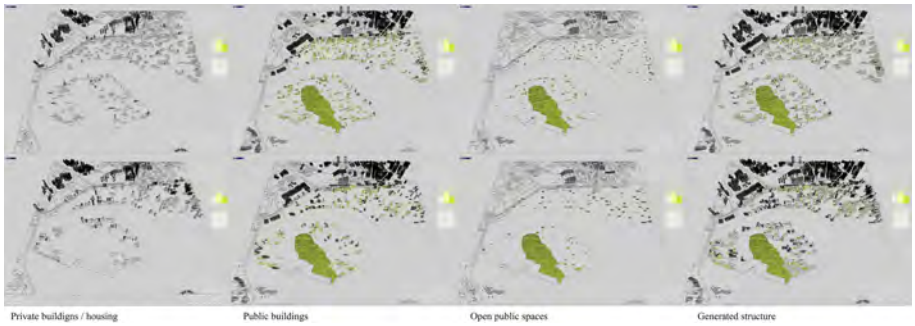


Figure 3. Various types of pre-defined urban configurations from Rhino appeared in the ABM model. The user is allowed to explore each urban activity separately.

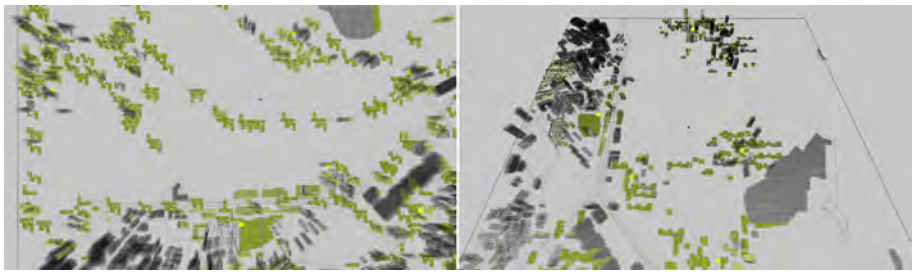


Figure 4. Generation of new buildings based on agents' flows and user-defined accessibility distances.

5. Conclusions

The proposed modelling framework allows the user to connect various applications (CAD, ABM model, visualisation window) by employing the middleware system LUCI which serves as a communication and data exchange platform.

5.1. DISCUSSION

For the time being, the proposed system has integrated an urban pattern formation algorithms dealing with urban mass and volumes only. Although the agents themselves are able to generate the buildings and patterns, the model is still limited in providing more precise street network layout. The visualisation of the model itself is simplified and expressed in a higher level of abstraction, but understandable for experts. Moreover, the model deals with the urban growth based on spatial requirements and it does not take into account broader aspects of urban metabolism. Nevertheless, the system can be enriched with more diverse modelling approaches as

the LUCI middleware allows it. The positioning of the agents and the urban mass need to be improved in order to obtain more rational urban patterns taking into account more realistic infrastructure and urban criteria of connectivity, visibility and centrality.

5.2. FUTURE WORK

By means of the proposed modelling approach introduced here, the planners, architects and stakeholders will prospectively identify the most significant processes within a city which influence the urban changes and might contribute to the phenomenon of self-maintenance, adaptability and self-sufficiency which can be characterised as processes of the urban autopoiesis. Based on these observations and external sources of information, the spatial urban solutions can be designed and assessed, showing more complex relational qualities of the urban space. Multidisciplinary approach of complexity science framework, consisting of computer science, urban design, Citizen Design science, and game development integrated into an advanced urban simulation and visualisation, will help experts to find more appropriate model of a liveable and adaptive city.

The research will continue in testing and developing the modelling and simulation framework linked with a visualisation system in a game engine (Cristie & Berger 2017) integrating aspects of urban self-maintenance and self-creation of urban patterns based on local conditions, communities' interactions, relay of external information (e.g. from social networks) and actual people's behaviour and tendencies in one urban design-modelling platform harnessing more complex urban phenomena.We would also like to use game engines as views potentially using Blender-based services to bake textures in real-time.

The system is open to be enhanced by more advanced algorithms, such as multi-objective criteria within urban synthesis methods as an input for the urban layout generation (König 2015). The proposed approach could contribute to the field of Cognitive Design Computing integrating more complex urban tasks and embedding artificial intelligence and recognition-based learning processes into the generative modelling workflow.

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FAMILIAR AND UNFAMILIAR DATA SETS IN SUSTAINABLE URBAN PLANNING

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Abstract. Achieving energy efficient urban planning requires a multi-disciplinary planning approach. The huge increase in data from sensors and simulations does not help to reduce the burden of planners. On the contrary, unfamiliar multi-disciplinary data sets can bring planners into a hopeless tangle. This paper applies semi-supervised learning methods to address such planning data issues. A case study is used to demonstrate the proposed method with respect to three performance issues: solar heat gains, natural ventilation and daylight. The result shows that the method addressing both familiar and unfamiliar data has the ability to guide the planner during the planning process.

Keywords. Energy performance; S3VM; decision tree; familiar and unfamiliar.

1. Introduction

In response to broad concerns regarding the environment and climate change, energy performance is becoming much more prevalent and increasingly in demand by occupants. URA (2012) pointed at these current challenges for Singapore: a) catering for economic growth and a good quality of life, b) maintaining a clean and green environment, and c) making the best use of our resources. Singapore has a tropical rain forest climate with no distinctive seasons; the typical day in Singapore has temperatures ranging from 23°C to 34°C and high relative humidity of about 84% (BCA 2010). Such high temperatures and humidity lead to a need to cool and dehumidify spaces to create comfortable conditions for occupants. However, the need for such climatic modification of spaces within a building consumes much energy. This has posed a great challenge for the buildings in Singapore to balance the energy performance with the responsibility to the environment.

To create an energy efficient urban fabric in Singapore that can not only minimise the impact on the environment, but also remain practical, economical and comfortable for use, it is important to look into integrated urban planning processes, as well as consider each aspect of urban space in an integrative and holistic

manner. More than 80% of Singapore's resident population live in public residential buildings. These buildings are developed and managed by the Housing and Development Board (HDB), and are all under temporary leaseholds. In order to reduce the energy demand of the residential estate, the initial plan establishes the orientation, massing and location of the buildings, all of which impact and set the parameters for energy efficient planning strategies. There are three primary issues to consider (BCA 2010, 2012; URA 2012):

1. Solar Heat Gain. Direct solar radiation increases the cooling load and hence energy use. In naturally ventilated spaces, solar heat gains heat up spaces such that they typically become thermally uncomfortable to occupants. The first step in minimizing solar heat gains is to optimize the orientation and massing of a project specific to its location. Certain orientations (east and west for example) provide more exposure to the sun and therefore greater heat gains. Also, the massing of a project could provide shade to itself or other blocks to further mitigate solar heat gains.
2. Natural Ventilation. Maximizing the amount of space to be naturally ventilated is another strategy towards reducing energy demand on a project since natural ventilation requires little energy use as compared to air-conditioning. Establishing and understanding prevailing wind directions and how they work on a specific site will affect massing and orientation decisions.
3. Daylight. It is also important to take advantage of and harness natural daylight for spaces. This reduces the need for artificial lighting which requires significant amounts of energy. Bringing in daylight via window openings at appropriate heights, skylights and/or atrium spaces are all effective strategies that will affect massing and orientation decisions too.

This research reconsiders multi-perspective planning data sets and classifies the data into familiar and unfamiliar groups with respect to the three primary issues outlined above. Semi-supervised support vector machines (S3VMs) are proposed in order to grapple with the familiar and unfamiliar data sets during the planning process. The proposed method includes the following steps:

1. Variables and parameters. The sufficient urban variables and parameters from the three issues are identified from literature review.
2. Similarity (Fréchet distance). The similarity between the familiar and other data variables (population, weather, economic, etc.) is checked.
3. S3VMs. Semi-supervised support vector machines are applied to these data.
4. Decision tree (C4.5). The planning decision is evaluated by the calculation of entropy (information gain ratio).

The method is applied to a simple case study and the result reveals that S3VMs have the ability to improve the data analysis to enhance the urban planning process. The remainder of the paper is organized as follows: first, the literature review is presented; next, the proposed method is described; subsequently, a case study for public housing is demonstrated by the method; finally, a discussion and future work are presented.

2. Literature Review

This section reviews the data methods for dealing with urban variables from an energy performance perspective.

2.1. URBAN VARIABLES

Following on the energy crisis from the end of the seventies, many design projects and researches were carried out to understand energy consumption for urban design. Knowles & Ralph (1981) discussed architectural and urban design applications from the variables of solar envelopes. Subsequent researches started to investigate the energy performance of urban design considering climate variables (Akbari & Taha 1992; Owens & Susan 1986). From the mid-nineties, designers and researchers begin to consider energy performance not only from a single perspective such as climate, morphology, etc., but also from multiple perspectives. They realized that the multifaceted relationship between energy performance variables and urban environment variables is the key to promote energy efficiency within urban practice. The whole urban system comprises many systems which are too complex to be quantified and represented in numbers and models (Yeang 1995). However, it appears there is no limit to include numerous variables into the analysis to quantify the urban impact on energy performance and vice versa. With the development of information technologies, the regression models for understanding design variables became more complex. Givoni (1998) and Littlefair et al. (2000) conducted research in both building and urban design located in different climate regions. They refined the design methods from an environment perspective and generated regression models for human comfort and the effects of urban form on climatology. Kikegawa et al. (2003) used the observed data with regression models to address the significance of regional meteorological conditions and its interactions with buildings on evaluating impacts of urban-heat-island on buildings' energy demand on a citywide scale. Ratti et al. (2005) pointed out that urban designers/researchers need to understand the building energy use as a comprehensive regression model of urban form, building design, energy system efficiency and occupant behaviour.

In order to address the abundancy of variables, new data analysis methods were proposed for the design process as well. Hanna (2007) implemented several techniques from machine learning and space syntax to define architectural archetypes. Liu & Seto (2008) built a method to simulate and predict urban growth from historical urban growth data. Gil et al. (2009) implemented a data mining method to extract descriptions of street and block typologies using attributes related to the morphology and density of urban blocks and street mobility. D'Oca & Hong (2014) developed a framework combining statistical analysis with two data mining techniques, clustering and association rules, to identify occupant behaviour patterns of window opening and closing in a naturally ventilated office building.

In conclusion, while supervised learning methods (regression models) are extensively used to deal with the abundance of design data/variables, and recent research explores the possibility of unsupervised (data mining) learning methods to handle with these kinds of data, there is lack of research on applying semi-supervised learning methods to grapple with both familiar and unfamiliar data sets.

2.2. DATA MINING

Data mining appears as a research discipline in the early 1990s (Piateski & William 1991). It is the core stage of the knowledge discovery process that is aimed at the extraction of interesting and implicit information from large data (Fayyad et al. 1996). Data mining can be considered a superset of many different methods: statistical methods and machine learning (Jackson 2002). Due to this sense, data mining could be categorized into 1) supervised learning (predictive), 2) unsupervised learning (descriptive), and 3) semi-supervised learning (predictive & descriptive). The goal of supervised learning is to learn a relationship between input and output data (Kotsiantis 2007). Unsupervised learning aims to find interesting structures in the data (Ghahramani 2004). The target of semi-supervised learning is to enhance the accuracy of both predictive and descriptive processes (Chapelle et al. 2006). The comprehensive fundamental methods and algorithms have been given elsewhere (Chapelle et al. 2006; Zhou & Li 2010; Zhu 2008). They identified the popular methods such as expectation maximization with generative mixture models, self-training, co-training, transductive support vector machines, and graph-based methods.

This research addresses the question whether semi-supervised learning is meaningful to solve the large data problems during the urban planning process. Specifically, in comparison with a supervised algorithm that uses only labelled (familiar) data, can one hope to have a more accurate prediction by taking into account the unlabelled (unfamiliar) data points? In principle, the answer is "yes". However, there is an important prerequisite: that the distribution of examples, which the unlabelled data will help elucidate, is relevant for the classification problem.

3. Research Methodology

The proposed method includes four iterative steps (figure 1): 1) Planning data sets. This data includes the influencing data from different domain subjects. 2) Similarity (Fréchet distance). The similarity between the familiar and other data variables (population, weather, economic, etc.) is checked. 3) Semi-Supervised Support Vector Machines (S3VMs). This classification method is carried out to separate the result of similarity as positive or negative energy performance. 4) Decision Tree (C4.5). All variables are recalculated by their information gain ratio with respect to the three issues: solar heat gains, natural ventilation and daylight. This result will help planners to identify which variable is the most important in the current planning stages.

3.1. DESIGN AND PLANNING DATA SETS

In order to demonstrate the proposed method clearly, the data sets are narrowed down to massing geometry variables and environmental variables, in relation to the three issues identified: solar heat gains, natural ventilation and daylight: 1) physical variables: massing orientation, massing height, massing location, site coverage; and 2) climate variables: solar, wind.

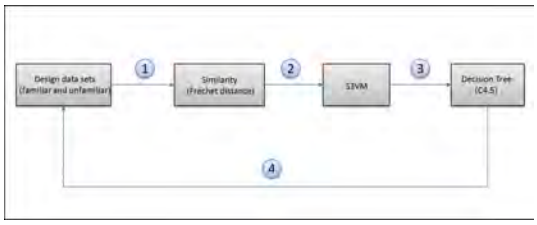


Figure 1. The four steps of proposed systemic method.

3.2. SIMILARITY (FRECHET DISTANCE)

The Frechet Distance was first defined by Maurice Frechet in 1906 as a measure of similarity between two parametric curves (Buchin et al. 2008; Eiter & Mannila 1994). Subsequently, it has become a standard measure between parametric curves used in many areas. The Frechet distance is typically explained as the relationship between a person and a dog connected by a leash walking along two curves and hoping to keep the leash as short as possible. The maximum length the leash reaches is the value of the Frechet distance. The standard definition for the Frechet distance (Alt & Godau 1995): Given two curves, A, B in a metric space, the Frechet distance, $d_F(A, B)$ is defined as

$$d_F = f_{\alpha,\beta} \max_{t\in[0,1]} \{d(A((t)), B((t)))\} \quad (1)$$

where α, β range over all monotone parameterizations and d(.,.) represents the Euclidean distance, and f is the infimum.

3.3. SEMI-SUPERVISED SUPPORT VECTOR MACHINES (S3VMS)

Semi-Supervised Support Vector Machines (S3VMs) are developed from Support Vector Machines (SVMs). SVMs rely on training data to generate a separating hyper plane that splits the given data into two different classes. SVMs are formulated into optimization problems in order to find a series of weights and a constant b, which together represent the separating plane. Such a decision boundary is defined as (Bennett & Demiriz 1999):

$$f(x) = w^T x + b \quad (2)$$

where w^T is the parameter vector that specifies the orientation and scale of the decision boundary, and b is an offset parameter.

However, traditional SVMs require the data to be labeled before classification analysis. Considering the limitation of the SVMs, this research adopts the S3VM to deal with the data during the design process, specifically, the software SVM-light (Joachims 1999).

3.4. DECISION TREE (C4.5)

The decision tree method C4.5 is proposed for the classification issues, because it adopts a simple hierarchical structure that aids user understanding and decision making. The C4.5 algorithm includes the information gain ratio concept, which is defined as follows (Quinlan 1993):

$$GAINRatio(p,T) = \frac{GAIN(p,T)}{SplitInfo(p,T)} \tag{3}$$

$$SplitInfo(p,T) = -\sum_{j=1}^{n} p'\left(\frac{j}{p}\right) \cdot \log\left(p'\left(\frac{j}{p}\right)\right) \tag{4}$$

where $p'\left(\frac{j}{p}\right)$ is the proportion of elements present at the position p, taking the value of the j-th test. The information gain ratio is independent of the distribution of examples inside the different classes.

4. Public Housing Estate Planning Case Study

We propose an estate planning case study at an empty site in the Punggol district of Singapore. From the URA master plan, the area has a maximum 3.0 stipulated gross plot ratio (GPR).

The proposed method assumes a distinction between familiar and unfamiliar data. To simplify the matter, the planners are assumed to be only familiar with parameters such as massing height, orientation, and locations. Instead, weather data (temperature, humidity, solar, etc.) and sociodemographic data (monthly income from work, marital status, age group, tenancy, household type, etc.) are grouped with the unfamiliar data sets. The design requirements reflect on solar heat gain, natural ventilation and daylighting. Therefore, planners need to understand the sun path and wind speed. In Singapore, the sun is almost directly overhead throughout the year since Singapore is located only 1º north of the equator. East and West orientations receive the most solar exposure and therefore have the most potential for solar heat gains. The Sun Path diagram for Singapore (figure 3a) indicates that both North and South orientations also receive solar exposure for a portion of the year. In Singapore, wind directions are predominantly N-NNE and S-SSE throughout the year depending on the monsoon season. Although Singapore generally has low wind speeds, the velocities achieved are enough to provide comfort to spaces with the help of optimised planning (figure 3b). In order to calculate the similarity, two vector curves are created: 1). Sun path curve as a horizontal line; 2). Wind direction curve line (N-NNE and S-SSE) (figure 4). Note that these two curves are only for illustration of the planning case; actual planning requirements may prescribe different curves.

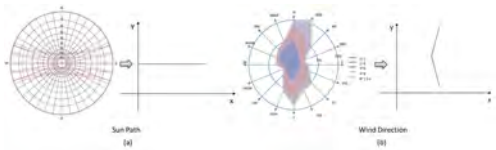


Figure 2. Singapore Climate. a) Sun Path diagram b) Annual wind rose (m/s) (1982-2015).

Considering the formulated curves, the planners begin to sketch the configuration with respect to either orientation, height or location. For instance, from a single massing sketch, the massing orientation can be identified. In the second step of the proposed method the similarity is calculated between the orientation curve and the two formulated curves (figure 2). The similarity is specified as a value between 0 and 1, with a smaller value indicating higher similarity. For the sun path, a higher similarity means the sketch plan has a low possibility to achieve energy efficiency at this stage. But for the wind direction, more similar curves represent a higher possibility to achieve energy efficiency.

The following step uses the software SVM-light (Joachims 1999) to determine which option is positive (high possibility of energy efficiency) or negative (low possibility of energy efficiency) clustering. The similarity of orientation is provided as familiar/labelled input data. At the same time, another similarity calculation between orientation and monthly energy consumption data is provided as unfamiliar/unlabelled input data. The monthly energy consumption data is based on HDB (Treelodge) which was awarded the Green Mark Platinum Award. The similarity results of the unfamiliar/unlabelled data help the S3VM to set the boundaries of positive energy performance clustering. Options 3 and 4 are clustered positively (figure 3). In the last step, the decision tree algorithm recalculates the similarity deviation between energy consumption and the solar heat gain, natural ventilation and daylighting variables. The planning parameters (orientation, height, location) are ranked by the information gain ratio of the similarity results. For both the third and fourth options, the decision tree lists the parameters in the order of location, height and orientation (figure 3).

Location and height can be determined in a similar way. The sketch of location is the sum of similarity of every single massing (figure 4); the curve of height is created by every massing's highest point (figure 5).

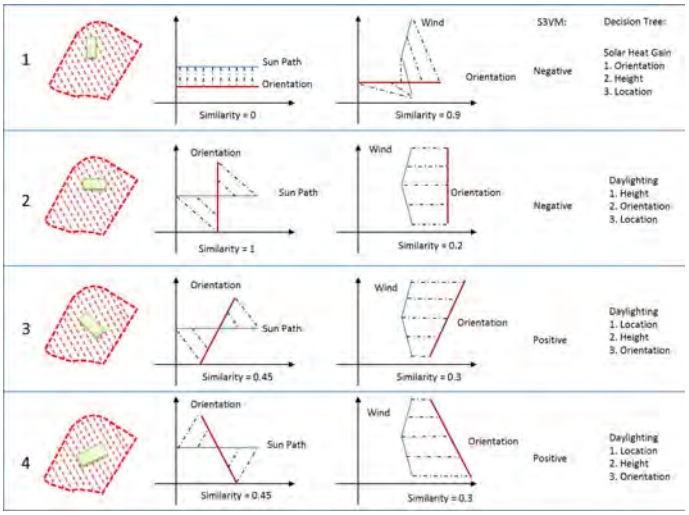


Figure 3. Frechet Distance calculation of orientation with sun path and wind direction. .

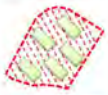
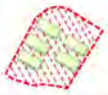
		Similarity (location/ sun path and wind)	S3VM location	C4.5
1		Sun path: 0.85 Wind direction: 0.85	Positive	Natural ventilation 1. Height 2. Location 3. Orientation
2		Sun path: 0.85 Wind direction: 0.85	Positive	Natural ventilation 1. Height 2. Location 3. Orientation
3		Sun path: 0.85 Wind direction: 0.25	Negative	Natural ventilation 1. Location 2. Orientation 3. Height
4		Sun path: 0.85 Wind direction: 0.25	Negative	Natural ventilation 1. Location 2. Orientation 3. Height

Figure 4. Locations from design draft.

		Similarity (height/ sun path and wind)	S3VM height	C4.5
1		Sun path: 0.85 Wind direction: 0.65	Positive	Daylighting 1. Shading
2		Sun path: 0.65 Wind direction: 0.65	Negative	Natural ventilation 1. Height 2. Location 3. Orientation
3		Sun path: 0.65 Wind direction: 0.55	Negative	Natural ventilation 1. Height 2. Location 3. Orientation
4		Sun path: 0.75 Wind direction: 0.75	Positive	Daylighting 1. Shading

Figure 5. Height from design draft.

The sequence of sketching and analysis illustrated in figures 3-5 does not have priority and can be altered by the planner. Considering the decision tree results, figure 3 could be linked to either 4 or 5 and vice versa. The process is also iterative; for the first option in figure 6, the decision tree also suggests to recheck the orientation. The trade-offs between different aspects are represented by the similarity values derived from the calculation step. This method reduces the burden of decision-making related to energy performance calculation for urban planners.

Comparing the final massing at this stage with the existing high energy performance HDB development in Singapore, we can conclude that the patterns of the massing design variables (orientation, location, height) are highly similar. This demonstrates that the proposed method distinguishing familiar and unfamiliar data has the ability to support planners/designers.

5. Conclusion

The objective of this research is to create a data analysis method to help the planner solve the multi-perspectives problems during urban planning. The proposed method mainly includes three parts: similarity calculation, classification (S3VM) and decision tree (C4.5). The important point is that the original data is separated into two groups: familiar and unfamiliar. The case result study reveals a typical residential planning pattern in Singapore. Hence it also proves the feasibility and possibility to apply this method into current planning processes. This demonstration is limited to the energy domain. Future research will extend the method to other perspectives: accessibility, traffic, etc. Additionally, the proposed method will be further developed to become readily usable as an urban planning support tool within research, education and, possibly, practice.

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URBAN PINBOARD

Establishing a Bi-directional Workflow Between Web-based Platforms and Computational Tools

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Abstract. Architecture is heading towards a future where data is collected, collated and presented in a dynamic platform. There is a potential for many standard processes in the industry to become automated, such as the site analysis process. Streamlining aspects of the design process allows architects to pay greater attention on creative design solutions for their buildings and less time engaging in complex, time consuming analytical programs. Urban Pinboard, a web-based GIS platform, promises to establish a bi-directional workflow between web data depositories and computational tools through the medium of a website. By doing so, the website allows users with minimal experience in computational processes to be engaged in the utilisation of these large datasets. Through the automation of these processes, relationships within the built environment industry can excel, leading towards performative driven designs.

Keywords. Urban Planning; Computational Urbanism; Data-driven Design; New Workflow Models; Software Development.

1. Introduction

Digitised data has been described as a dynamic and flexible technology that is fundamentally transforming our society as outlined in 'The Second Machine Age' (Brynjolfsson 2014). Reflecting upon industry challenges that architecture faces in the digital age, information data is scattered throughout the internet, estranged from correlation and relationship. This is a challenge for the AEC (Architecture Engineering Construction) profession as, due to its large number of different stakeholders, large quantities of data are involved in completing a project. Yet, if this

data was unified and composed, it could greatly assist architects in their work and support their productivity, freeing them from manual data collection and analysis and enabling them to focus on different aspects of the design process.

In the built environment, data is mostly stored in Geographic Information System (GIS) models, which store and display spatial information in relation to specific positions on the earth's surface. Here, large data sets of urban and geographical information exist, however, a common issue for architects and designers is that these data sets are either inaccessible (no open source GIS data is yet available in Australia - however data sets are being increasingly built in the US), or are associated with large costs when embedded in commercially available GIS software packages. The background for these limitations is that data sets have only recently been made public through open source and through a new Australian government e-planning initiative. These large data sets of geographical information will become available for free, but on individual platforms, mainly each author of data will host their data on their website. example?

Consequently, one can argue for a need to collate this existing data within a single centralised data depositary (Picon 2010). This 'need' in the industry has been addressed in Australia through the emerging platform Urban Pinboard - a digital platform currently in development by the research team under commission and enabled through a 'City Life Lab' grant from the Urban Development Institute of Australia (UDIA). Urban Pinboard is a new tool for collaboration that connects the public, private and community sectors in a single conversation with innovative digital technology to drive smart city transformation. Urban Pinboard will be also unique and powerful because, unlike other one-way e-platforms in use around the world, it will allow these three sectors to not just access data but also exchange their ideas, thus creating a real and powerful feedback loop. Hence it can be considered as a library of open urban data, represented graphically in a global map interface. The platform creates an interface between unreadable datasets and its users such as government policies, survey information and development proposals. Consequently, we argue that Urban Pinboard has the potential to unlock communication barriers through technology, and produce accurate data flows where site potential can be determined through a dynamic platform. This notion is backed up by As and Schodek (2008) who state, *'The way in which we visualize architecture, directly by graphical representation methods, affects the way we design and perceive architectural form and performance.'*

2. Research Project

Yet, Urban Pinboard as well as other currently available open data sets on the internet are not linked to computational programs such as Rhino and Grasshopper. Thus, the multitude of data can often not be utilised via commonly used and readily available computational design tools, but by bringing the open data set platform and computational design tools together, one could unite and streamline current practices. Hence, the study aims to create a bi-directional pipe between web-based data depositories and the computational tool, Grasshopper. Having a website as the interface for computational processes would allow users, who aren't necessarily trained in computational design or architecture, be able to control the

information that they want to see in a simplified, graphical format. An interface for decision making allows a process oriented experience for the user (As & Schodek 2008) and further as argued by Huang and Krawczyk (2007) *'Ideas of what constitutes a design experience are expanding. Different opportunities for designers and consumers are opening up as control over design decision making is no longer entirely in the hands of the architect.'* Furthermore, creating an Application User Interface (API) for the pipe within Grasshopper would allow developers who are computationally skilled, to create customised scripts to apply to these large data sets. As a proof of concept, we will be creating a shadow analysis tool in Grasshopper, however the data 'pipe' is the central exercise (figure 1). From knowledge of Javascript and Python to construct the 'pipe' to Grasshopper, strings of data can be transported to one platform to another, used in Grasshopper's analysis, and sent back to Urban Pinboard in a graphical format.



Figure 1. A diagrammatic representation of the bi-directional pipe, connecting web-based data depositories and Grasshopper.

3. Methodology

Drawing on knowledge in web-based rendering (Altabtabai & Yan 2007), e-planning initiatives and the scripting languages JavaScript and Python (Kostadinov 2006), the research used an agile method to develop and test the proposed pipe in parallel and preparation of Urban Pinboard's development. The objectives of the developed Python based pipe are to:

- Enable a user to select a specific geographical area with a mouse selection on a website,
- Feed data associated with the selected area via the 'pipe' to Grasshopper,
- Compute the result in Grasshopper,
- Send back the results through pipe to Urban Pinboard as rendered 3D objects.

As a proof of concept, the research is using the open-source environmental analysis plugin Ladybug for Grasshopper to create the shadow analysis tool. The paper concludes and argues that a direct link between these two platforms would benefit both, client and architect. This is based on the hypothesis that

- Unlocks potential communication barriers established through technology,
- It produces accurate data flows where architectural sites potential can be determined through a dynamic platform, and
- Streamlines and analyses data sourced from online data depositories.

Hence, offering a new automated means of delivering urban design outcomes and providing more context about the geographical area selected by the user. This provides instantaneous, site-specific information that has the power to revolutionise the industry, streamlining previous practices.

4. Development Steps to Establish the Data Pipe

To develop the pipe, the application will use Python Flask (2016), a micro web framework to host the site. HTML and CSS files are linked in to create the visual display and functionality on the client's side. Using Flask allows the application to use the flexible programming language Python to create the data pipe and transport information sourced from web data depositories.

4.1. STEP 1: ENABLE A USER TO SELECT A SPECIFIC GEOGRAPHICAL AREA WITH A MOUSE SELECTION ON A WEBSITE

At the time of the submission of the paper (October to December 2016) Urban Pinboard was not yet fully functional as the launch date of the beta version is scheduled for end of March 2017. Consequently the research team had to test its hypothesis on another, still similar big data depository platform. Based on research conducted during the development of UrbanPinboard the developer platform of Mapbox (2016) has been identified as he preferred big data depository source. Mapbox is used across the industry to visualize and create interactive maps. Using the Javascript library and the API of Mapbox, one can extract the information required to conduct the site analysis in Grasshopper. As our proof of concept, the research will be extracting the latitudinal and longitudinal of a clicked site to create a visual sunlight hour analysis.

Previously, only building footprints could be viewed in Mapbox, however recent development has enabled users to extrude these building footprints to represent their real-life counterparts. This building height data is yet only widely available in areas such as the US and the UK, so the research team has chosen to locate the case study project in San Francisco.

4.2. STEP 2: FEED DATA ASSOCIATED WITH THE SELECTED AREA VIA THE 'PIPE' TO GRASSHOPPER

When the user clicks a geographical point on the map, the website needs to save the Latitude and Longitude of that point. Using JavaScript, one can define a function to perform on a click action. Using the Application Programming Interface (API) of Mapbox one can then access the latitude and longitude at that point. Assigning this to a variable enables the user to use this data at a later point in the code. If the user decides to click elsewhere, the function runs again and the variable is assigned the new latitude and longitude.

As Mapbox delivers this as an object, one must reformat this data to a JSON

string so it can be sent through an AJAX function to the server, and ultimately to Python. When the 'Post' button is clicked, an AJAX function is executed, sending the data as a JSON to the server. On the Python side, now one must request this data that has now been uploaded to the server. Using a 'get' request action, the string uploaded to the server can now be used as a variable in Python.

In a next step the user must save this JSON data to a file so that Grasshopper may open it and use its location information to perform site specific analysis. The code opens a file called 'json_test.JSON' and re-writes its contents to the value of 'myJson'. Therefore, every time the client clicks 'POST' and uploads new data to the server, the file is automatically re-written and a different analysis is performed in Grasshopper.

4.3. STEP 3: COMPUTE THE RESULT IN GRASSHOPPER

Our research has unveiled that the process of reading the JSON file in Grasshopper is quite simple. It involves using the 'Read File' component to read the text document, bringing the string into Grasshopper. Once the latitude and longitude coordinates are brought into Grasshopper, they need to be converted into Universal Transverse Mercator (UTM) coordinates to construct a point within Grasshopper. This is because digital workspaces such as Rhino are based off a flat infinite grid, whereas longitude and latitude are used to represent the earths surface as a spherical object. UTM coordinates are used to represent the earth in two dimensions. It is the projection system used for Google Maps and OpenStreetMap. Converting between these coordinates is a complex process involving multiple calculations. Rather than trying to deconstruct these calculations we considered automated conversion systems that were readily available on the internet.

There is a variety of packaged python libraries that contain latitude / longitude to UTM conversion functions within them. 'Pryproj 1.9.5.1' (Whitaker 2016) and 'utm 0.4.1' (Bieniek 2016) are the most common packages that are readily available. By using the python libraries, the complex process of conversion can be simplified to a line of script and can be embedded within Grasshopper. Once the UTM coordinates are created they can be used as XY coordinates to construct a point in Grasshopper.

In a next step the buildings and topology of San Francisco were brought into Grasshopper using Flux Site Extractor (2016) as meshes using the Flux plugin for Grasshopper. With the point from the pipe contextualising the site, we can create multiple tools within Grasshopper, providing an automated analysis of the site. In this case, we are constructing a shadow analysis tool.

The point constructed in Grasshopper representing the users click, can be used to select the closest building footprint. This is done using Grasshopper's native component called 'Mesh Closest Point' which finds the closest point projected on a mesh in relation to a search point. Using the input point from the user as the search point, the distance between the point and the surrounding building meshes can be found. The list of distances is then sorted numerically, and the shortest distance is used to define the building the user has selected. The surrounding context is chosen using the same distances, and applying a 'Smaller Than' component to

filter out the buildings which are outside of a variable distance. For example, if the variable is set to eighty meters, any building which is within eighty meters of the user input point will be selected.

Using the building selected by the user, and its surrounding context, one can now begin to create an analysis to feed back to display on the website. Using the EPW weather file of San Francisco, Ladybug can generate sun vectors based off a time of year and range of hours. These vectors and the building meshes selected by the user can be analysed using the 'Ladybug_Sunlight Hour' component, which calculates the number of hours of direct sunlight received by an input geometry. The component analyses each mesh face in an input geometry and outputs the number of hours of sunlight received each face as a list of numbers. The component also creates a coloured mesh which visualises this sunlight information. Therefore, the more mesh faces that the input geometry has, the more accurate the analysis will be. However, rebuilding the meshes with more mesh faces slow down the processes speed as each face needs to be calculated individually for sunlight access.

Once Ladybug has calculated the hour of sunlight on each mesh face, the meshes need to be transformed into a format that is suitable for web-based platforms. Wobbegong, is a plug-in for Grasshopper that is currently in development. It creates scalable vector graphic (.SVG) files using curves and polylines directly in Grasshopper, the graphics are style using cascading styling sheets (CSS) which are also defined within the Grasshopper environment.

The first step in using the API for Wobbegong, is to create a layout using the 'SVG Plane by Page' component which uses a plane, page size and scale as its inputs. The mesh created from the analysis needs to be oriented within this layout and all mesh faces need to be converted to polylines. Polylines can be converted into SVG scripted geometry using the Wobbegong component called 'SVG Polyline'. The input for this component includes defining the class which associates how the polyline will be styled using CSS. The 'CSS Style Maker' component allows the styling of SVG based off different classes and outputs a style sheet. Options for styling include stroke thickness, colour, fill, opacity and line type. By allocating a different class to each mesh face we can associate a different fill colour in the SVG (figure 2). It's important to note that the order in which the layers are sorted is associated with the order they are layered in the SVG. Items that appear first in a list appear underneath objects which are later on in the list.

To create a top view plan of the analysis, only the roof top mesh faces need to be visualised. This requires the need to remove any unnecessary or unseen mesh faces to display in the SVG file. To do so the centroid of each mesh face was deconstructed and sorted by height. The points which were highest in each building geometry were defined as the top faces of the geometry. Anything lower that the highest points of the geometry were culled out of the list and not used to create the plan view of the analysis.The classes used to define the mesh colours were based off the output of the 'Ladybug_Sunlight Hour' component which gives the hour received by each mesh face as a number. Since both the list of polylines and numbers are respectively listed. The number of sunlight hours were remapped through a gradient which converted the numbers into RGB colours.

A similar process was used to create 3D perspectives of the analysis mesh. The

mesh faces were ordered based off their closest distance to the XY plane. After the SVG and CSS are created they are used as inputs in the Wobbegong component called 'HTML Complier' which exports both as a single html file which can be viewed in web browsers.

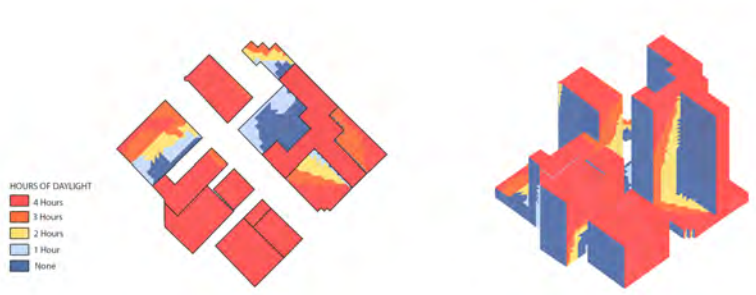


Figure 2. SVG outcome of sunlight analysis in plan (left) and perspective view of Sunlight analysis in SVG (right).

4.4. STEP 4: SEND BACK THE RESULTS THROUGH PIPE TO URBAN PINBOARD AS RENDERED 3D OBJECTS

When Grasshopper has finished its calculations, and has rendered out and saved a SVG file, Python must know how to look for a file and then return it to the server. A 'while' loop in Python uploads the rendered image to the server when that file begins to exist. If the file does not exist yet, the 'else' statement is executed and a placeholder image is uploaded, telling the client that no calculations have been performed yet.

At any one point, an image will be uploaded to the server. The image will change when Grasshopper completes its calculations and saves the rendered images, which will trigger Python to load that picture to the server. What SVG is uploaded to the server, however, must be received and inserted into a container for viewing for the client. The opposite of an AJAX Post, the Get function receives the SVG for use in the HTML. If the Get function is successful, the SVG is serialized to a String and inserted into the inner HTML of the 'Content' container. This function is wrapped in a 'setInterval' function, which refreshes the AJAX Get method every three seconds, allowing for the website to be updated dynamically. As Urban Pinboard was not in function at the time of submitting the paper figure 3 shows the rendered result NOT in the 3D urban model, this is what Urban Pinboard will offer when completed.

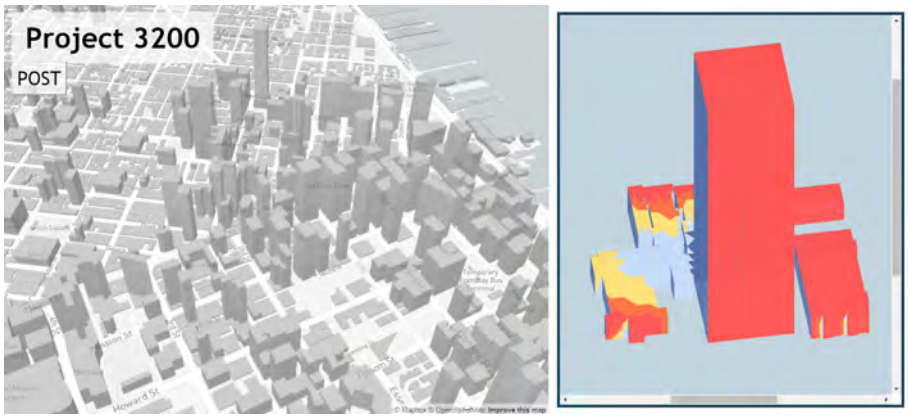


Figure 3. When Grasshopper has finished its calculations, the placeholder image is dynamically swapped out for the rendered SVG. .

5. Significance of Research

Based on research and literature reviews, as well as through the practical experimentation within the research's industry partner, Cox Richardson Architects Sydney, we can conclude that Urban Pinboards new transference of data between platforms has the potential to streamline and inform the industry, with huge a potential impact. This statement is based on the observation that:

Firstly, communication barriers between web-based data depositories and analytical computational design software can be broken down through new and emerging programming methods, using Javascript and Python. Individuals, such as architects and clients, with minimal or no computational design background, will be able to use this simplified interface system to access diverse processes and information, which was previously unavailable to them. Using this web-based tool in an architectural work environment would potentially cut the cost of manual analysis and economize on time. In summary, the techniques illustrated by this research have the potential to lower costs in two senses: first, it will lower the amount of expertise required to access a complex digital process and secondly, it will lower the financial cost of accessing that process.

Thirdly, due to the reduced cost in accessing design processes, Urban Pinboard has the potential to act as both - a unifying and dividing force within the architectural industry. It will unify the industry by facilitating better data sharing and widely distributing state-of-the-art processes as soon as they are written (by publicly exposing these processes as APIs). It also has the potential to divide the industry by dividing firms into smaller pieces. Lower communication costs will mean that clients can divide a design brief into portions, and give each portion to a separate firm without dramatically increasing design cost. For example, a client will likely be unwilling to pay an architect for a days work producing a shadow study if one is able to obtain the shadow study with one click. Smaller communication overheads has further the potential to change the composition of the architectural

services market to be comprised of smaller, more specialized firms collaborating inexpensively on a shared model of a building

Finally, changing a workflow to Urban Pinboard in combination with Grasshopper through the developed pipe can save a firm (and therefore a client) time and money on, environmental analysis, such as a shadow study. This causes design processes to be streamlined, and the architect can focus more on an informed, design-driven outcome. Since this kind of algorithmization of architectural workflows produces analysis more cheaply than other methods, it is likely that market pressures will push more firms to create these kind of workflows. In that regard, this project also demonstrates impressive scalability: the research team have further developed a data pipe-way to streamline site analysis to the click of a button at a cost of time that is not prohibitive, and could be widely adopted. There is good reason to believe that this method of data interactivity can be further developed to produce more diverse architectural analyses and processes, extending the presented case study of solar and shading. This is subject of upcoming research between the industry partner and academia.

6. Conclusion

This paper outlines the value of digitised data sets in the industry with the use of computational tools, by using an agile method to test and develop a 'pipe,' connecting open sourced data depositories to Grasshopper. Creating this interconnectivity between web data sets and computational programs in a new bi-directional web-based tool has the possibility to change the industry and its practices. Increasingly visual and direct communication processors have the potential to create a large cultural impact in the interaction between the architect and client by lowering the barriers - both in terms of expertise and finance - between client and architectural process: increasingly the client communicates directly with algorithms and the architect is evermore the author of those algorithms.

The introduction of this new workflow model into the field would permit greater consideration in design driven outcomes, unlock communication barriers with technology and enable more rigorous and considered design without a significant increase in cost.

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FRACAM

Cell Phone Application to Measure Box Counting Dimension

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Abstract. There are two kinds of algorithms: those that are 'better' with respect to accuracy and those that are 'faster'. In the past, fractal analysis by means of box-counting - including both, binary and greyscale analysis - has been focused on the former. In our work, however, we want to aim at the second category: algorithms that are fast and easy to use, without losing view on significance. To this end we have devised a cell phone application which let users grasp and analyse photographs regarding the box-counting dimension of e.g. facades. The application includes two measurement methods for binary images, based on threshold conversions, and one for greyscale images. Accuracy has been tested on deterministic fractals with known fractal dimension. As a matter of fact we are able to produce what was formerly constraint to scientific implementations or discourse on every day's hardware.

Keywords. Fractal analysis; Differential Box-counting; Fractal dimension; Cell phone application.

1. Motivation

Fractal dimension is an indication for the roughness or the irregularity of natural or artificial objects. Among others, box-counting, which is a fractal analysis method, is one of the easiest ways to estimate the fractal dimension and suitable for the study of complex objects. Since Carl Bovill applied box-counting for the first time to architecture (Bovill 1996), it has become widely used in this field (Capo 2004; Zarnowiecka 2002; Rian et al. 2007; Ostwald & Vaughan 2016). It enables the possibility to analyse and compare geometric properties (Ostwald & Vaughan 2016). From a methodological perspective, it enables to visualize the development of roughness across multiple scales, which allows, for example, to draw reliable conclusions about whether or not a harmonic relation between the whole and it parts exists (Lorenz 2013). Studies have shown that box-counting provides an objective comparison method between different design solutions (Lorenz

2013) or give a more precise picture of design intentions (Lorenz 2014). Fractal analysis has also been used to test hypotheses about social, stylistic and personal trends in design (Ostwald & Vaughan 2016). Since all these studies are focused on binary box-counting, they only take plans (line graphics) into account. However, there are two main disadvantages about a binary implementation: first, because elevations have to be prepared for calculation beforehand (e.g. redrawing as vector graphics, applying edge detection or line width reduction) the method is time consuming and second it is used, so to speak, "in the office" but not "on the street", which much better corresponds to the natural environment of buildings. Unlike other techniques, which are based on fractal analysis methods, the main goal of the here described approach is both, convenience and speed of the computer program. Moreover, everydays usage is an important matter, which is the reason why a cell phone application has been developed. The application comprises the box-counting algorithm for binary images - which includes threshold conversion of photographs beforehand - as well as the differential box-counting algorithm, which is applied to a greyscale image right from a camera shot. Differential box counting-based approaches are so far used for analyzing texture features and texture classification (Filho 2008; Sankar & Thomas 2010; Gao et al. 2016), which will enlarge the previous insights of geometric properties in architecture. Due to the fact that fractal dimension, on the one hand, is (to a certain extent) sensitive to the method used and, on the other hand, can be the same for different textures, the authors propose different fractal analysis methods, which will be implemented step by step. This enlarges the possibility to answer research questions about harmony, design intention and possibilities of comparison. The webpage with the current state of implementations is available for test purposes under: www.iemar.tuwien.ac.at/processviz/fracam/ (Wurzer & Lorenz 2016). The target groups are researchers that use fractal analysis methods for classification and scholars to recognize and to get a feeling for the connection between scale and harmony.

2. Background

Benoît Mandelbrot formulated the theory of fractals, generally speaking, in order to understand and describe the irregularity of nature: the roughness in the shapes of clouds, mountains, coastlines and bark (Mandelbrot 1975). A core message of the "new" theory is that natural objects, such as coastlines, cannot be described by simple primitives (cones, spheres, cubes) and that natural objects rather follow the concept of self-similarity. When B. Mandelbrot (1967) asked for the length of Britain, he thus pointed out the lack of Euclidean geometry to analyse and describe natural forms. As consequence and in order to give irregularity a proper value he introduced the term fractal dimension (Mandelbrot 1967), which is based on the definition proposed by Felix Hausdorff (1919). The Hausdorff dimension of a fractal can be a non-integer value and is strictly greater than its topological dimension (Mandelbrot 1983; Falconer 1990). In 1983 B. Mandelbrot (1983) described a fractal analysis method in order to estimate the fractal dimension (capacity dimension) of objects located in the two dimensional plane; today the method is known as box-counting. According to C. Bovill (1996) the method provides a possibility

for quantifying characteristic visual complexity. Since C. Bovill published the first results of applying box-counting to architecture most of the researches in this field uses the method as described there (Bovill 1996): A grid is placed over a black and white (binary) line graphics whereby all boxes (cells) that contain a part of the image are counted; in the next step, the grid size is reduced and boxes that contain a part of the image are counted again; this results in data points with the number of covered boxes versus the grid size; finally, the characteristical value - the box-counting dimension (formula 1) - is determined by the slope of the regression line in a double logarithmic graph.

$$D_B = \lim_{\epsilon \to 0} \frac{\log N_\epsilon}{\log\left(\frac{1}{\epsilon}\right)} \tag{1}$$

Although the method is an efficient approach to estimate fractal dimension, it is subject to various influences, such as linewidth, starting box size, grid position, grid reduction factor and selection of representing lines (Fourtan-Pour et al. 1999; Lorenz 2012; Ostwald 2013). Most important with the described arrangement is that not the original building is analysed, but a two dimensional representation of it, e.g. the elevation. It is a line graphics that represents the design intention of the building rather than the actual status. Due to the influence factors coming along with the method itself, a meaningful statement is only possible if measurements of different settings are analysed. That leads to a set of significant (statistic) values of the set of measurements: the median; the interquartile range (IQR, which describes the accuracy of the whole set); the smallest and the average coefficient of determination (R^2, which describes the deviation of single measurements); and the range of scale (which equals the range of coherence) (Lorenz 2016). In order to minimize the influence of line width, vector graphics (e.g. AutoCAD files) can be used instead of raster graphics (Lorenz 2012). However, both, to analyse vectorized images as well as to calculate a whole set of measurements leads to an increased time consumption. Unlike the described approach the authors introduce a fast method applied to photographs.

3. Greyscale Box-Counting

So far, architectural research used fractal analysis methods exclusively in order to examine two dimensional representations of buildings, mainly facades. Such an approach takes primarily the design intention into account, but not the is-in-use state. The authors want to fill this gap and go a step further by expanding the binary information using greyscale images. Thus additional information is taken into account, mainly expressed by contrast (light and shadowing, intensity of colours). Since this approach still analyses 2-dimensional representations it is only one more aspect on a comprehensive holistic analysis of architecture using fractal analysis methods. It is a part of the chain of possibilities also including rescaled range analysis that determines the fractal characteristics of rhythmic structures (Bovill 2000). While binary images or line graphics (elevations) allow a quantitative analysis of the shape, greyscale analysis rather concentrates on the texture. In order to analyse greyscale images, basically, two different methods are possible: either the representation is converted into a black and white image, using the same algorithm as

described before in “background”; or the “grey” intensity inside the boxes is taken into account instead of just measuring the covered boxes. The latter method means, subsequently, to adapt the algorithm itself.

4. Box-counting and Threshold

In order to analyse greyscale images with the original box-counting method, the value of the threshold used for conversion is crucial. In practise, the value divides the image into the set that is important and its background (black and white points). Following this approach, a first implementation of the program (called *Single threshold*), simply said, converts the greyscale image at different thresholds (e.g. 12.5%, 25%, 37.5% and so on) and measures in each case the box-counting dimension.

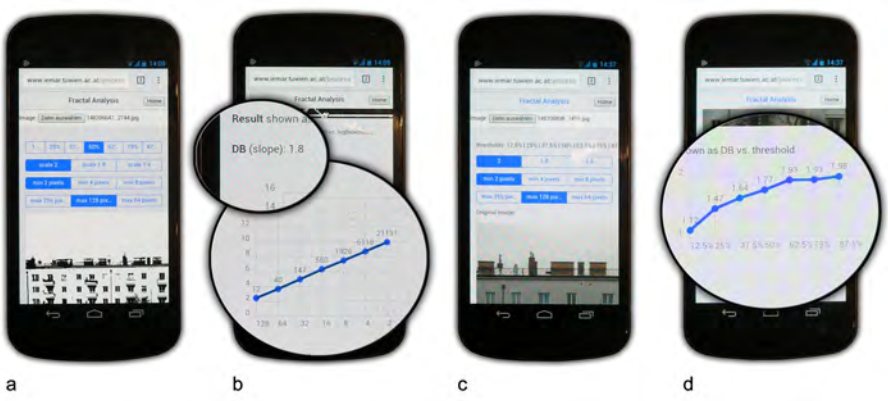


Figure 1. Threshold conversion of a greyscale image and box-counting measurement as cell phone application. 1a: settings of the basic implementation (‘Single threshold’); 1b: double logarithmic graph with regression line and slope (DB); 1c: settings of the advanced implementation (‘Different thresholds’); 1d: results (DB) of different thresholds.

With focus on a fast result, the considered photograph is, at first, converted into an image of 512 Pixels width. The user then chooses the favored threshold from a list of possibilities (50% by default), which converts the original photograph into a black and white binary image (figure 1a). Concerning the measurement itself, the algorithm starts with a grid size of 128 Pixels (which is 1/4th of the overall width). This first grid is placed over the image and the boxes that cover the foreground are counted. Thereafter the grid size is halved (according to the default reduction factor of one half), leading to a box size of 64 Pixels and the boxes are counted again. This procedure is repeated until the smallest allowed box size of 2 Pixels is reached. Not only the smallest and the largest box size can be adjusted, but also the reduction factor can be changed to predefined values (which may slow down calculation because of additional box sizes). The result of calculation itself is visualised as a double logarithmic graph with *log(box size)* versus *log(number of covering boxes)*. Finally, the slope of the regression line defines the box-counting dimension (figure 1b).

The modification of the first implementation, called *Different thresholds*, automatically repeats the previously described algorithm for different predefined thresholds (currently running from 12.5% to 87.5%). The outcome is therefore not a single value, but a set of box-counting dimensions (of different threshold values T_i; $i\epsilon 1 \ldots N$). This specific set characterises how roughness changes as threshold increases. Following from that, it is the tendency that characterises the texture signature (formula 2; Backes & Bruno 2008).

$$\psi(A) = [D_B\ of\ T_1,\ D_B\ of\ T_2,\ \ldots,\ D_B\ of\ T_N] \quad (2)$$

Both implementations (the *Single threshold* and the *Different thresholds*) were tested with deterministic fractals, i.e. fractals that are constructed in an algorithmic way and which are defined as the attractors of certain iterated function systems (Barnsley et al 2005): the Sierpinski gasket, the Minkowski curve and the Koch curve. With Sierpinski gasket, for example, an equilateral triangle (the initiator) is subdivided into four smaller triangles of half the size. The middle part, which arises from connecting the midpoints of each side, is removed. These steps are repeated on the three remaining triangles and so forth. It is obvious that after infinite iterations (applying the rules repeatedly on the output) the final object is exact self-similar. That means zooming in on a detail offers the same structure as the whole. It is thus possible to calculate the so-called self-similar dimension (formula 3):

$$D_s = -\frac{\log(N)}{\log(\epsilon)} \quad (3)$$

with 'N' equals the number of remaining pieces and 'ϵ' equals the reduction factor. For Sierpinski gasket the number of remaining pieces is three and the reduction factor is one-half. Substituting these values into equation (3) results in the self-similar dimension D_s=1.58. For the test case seven iterations of the Sierpinski gasket were drawn in a CAAD software and exported as an black and white image with 512 pixels width and 72 dpi resolution. Based on default settings, the basic implementation *Different thresholds* results in constant box-counting dimensions of D_B=1.56 for all thresholds, which is only slightly lower than the calculated D_s=1.58. The same holds true for a drawing of six iterations of the Koch curve (D_B=1.23 and D_s=1.26) and a drawing of six iterations of the Minkowski curve (D_B=1.44 and D_s=1.50). Testing all measurements possibilities, the best results are achieved for Sierpinski gasket with the following settings: scale reduction = 1.8, smallest box size = 4 Pixels and largest box size = 256 Pixels. In this case all values equal the self-similar dimension (D_B=1.58 and D_s=1.58) (figure 2).

Standard examples which are well known from image analysis and image compression act as greyscale test images: Baboon, Bird, Cameraman and Lena. As expected, this time the results increase from the first (smallest) to the last (largest) threshold, since more and more grey values are turned into black points and hence counted. What can be observed is that the curves differ from each other, which, in turn, characterises the texture signature (figure 2).

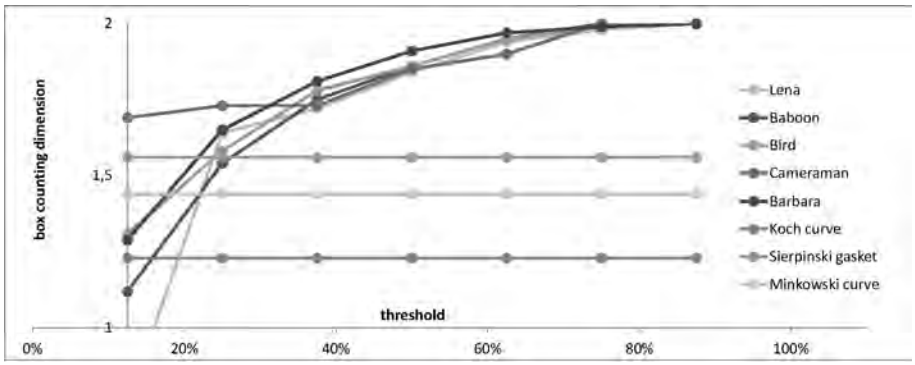


Figure 2. Results for different predefined thresholds of deterministic fractals: Koch curve, Sierpinski gasket and Minkowski curve. And examples of texture signatures for standard examples: Baboon, Bird, Cameraman, Barbara and Lena.

5. Differential Box-counting

An extension of the standard box-counting method directly takes greyscale images into account and by that makes a conversion to binary black and white images obsolete. The so-called differential box-counting (Sarker & Chaudhuri 1994) is currently used for discrimination between textures from urban areas (Filho 2008) and in medicine, e.g. to detect cancer (Sankar &Thomas 2010; Gao et al. 2016). Basically, differential box-counting regards an image of size M x M pixels (x-, y-coordinates) as a three dimensional landscape, whereby the z-coordinate indicates the grey level: with lighter pixels forming mountains and darker pixels defining valleys. Similar to the "standard" box-counting method a grid is placed over the image, with the box size (s) limited to the given range $M/2 \leq s \leq 1$ (with s as an integer). Consequently, the ratio equals $\epsilon = s/M$. Each cell of the grid consists of s x s x s' boxes with G/s'=M/s (with G equals the total number of grey levels). Unlike the binary analysis, which only checks whether or not a cell contains a part (a pixel) of the image, differential box-counting calculates for each cell (i, j) of the grid the difference between the box number in which the minimal grey level falls and the box number in which the maximum grey level falls (Figure 3a). The difference is calculated by

$$n_\epsilon(i,j) = l - k + 1 \tag{4}$$

with 'k' equals the box number of the minimal grey level and 'l' equals the box number of the maximum grey level. Finally, the total number of counted boxes for each grid size covering the full image surface is given as

$$N_\epsilon = \sum_{i,j} n_\epsilon(i,j). \tag{5}$$

The differential box-counting dimension D_{BC} is, finally, calculated as given in equation (1) and determined by the slope of the regression line in a double logarithmic graph. Figure 3b shows the related regression line of plotting $\log(N_\epsilon)$ versus $\log(\epsilon)$, as coming out from the cell phone application *Greyscale*. Since

the difference between intensity is calculated, in some sense, the method uses an approximation of the thickness of the covering surface.

Following from above, differential box-counting regards a greyscale image of size M x M pixels. Thus the algorithm starts with a conversion of the image into 8 bit greyscale (256 grey levels) and a reduction and/or cropping in order to fulfil the requirement of a squared image size. As with the aforementioned applications the calculation method encompasses a default range of box sizes from 128 to 2 Pixels. However, the user interface offers, once more, the possibility to change the smallest and largest box size (figure 3b).

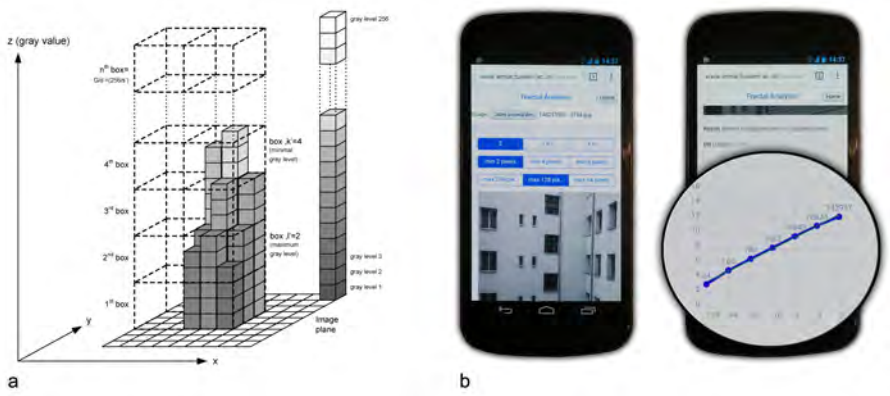


Figure 3. Left 3a: Schema of the differential box-counting method for s=3 and s'=3, determining 'l' (box number of the maximum grey level) and 'k' (box number of the minimal grey level). Right 3b: Settings and result of the 'Greyscale' application.

The applied method has been tested with *experimental* cases, and, once more, with standard examples (Baboon, Bird, Cameraman and Lena). *Experimental* cases are those that fulfil certain *extreme* characteristics. Theoretically, the differential box-counting dimension is always between two (very smooth) and three (very rough); i.e. the rougher an image is, the closer the value is to three. Hence it is expected that D_{BC} for a monochrome image (completely filled with white, grey or black) is close to two. Whereas a black and white chess field like image (with a field size of 1 Pixel) offers the greatest possible difference of N_ϵ leading to a theoretically result of three.

The size M x M of all test images equals 512 x 512 Pixels, while the total number of greyscale *G* equals 256. As can be seen from figure 4 all *experimental* cases achieve the previously described values. Whereas those of the standard examples offer different results between two and three, depending on their roughness.

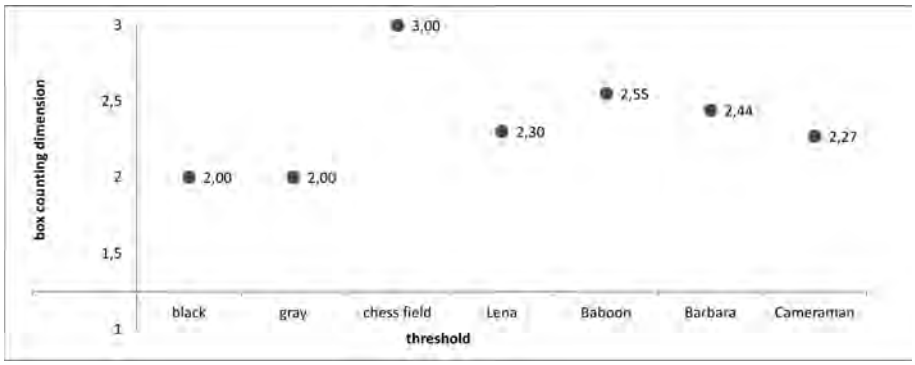


Figure 4. Results for experimental cases and examples of texture signatures for standard examples (Baboon, Bird, Cameraman, Barbara and Lena).

6. Interpretation of the Results

The building's fractal dimension, as a characteristic value of roughness is, in any case, only reasonable if the result is compared with those of other buildings. Apart from this, since all used methods are subject to influences inherent to the technique itself, it is important that only results of the same method are examined. As a consequence we recommend not to look at each individual measurement in isolation, but to consider it as a part of a "self-contained" comparison system. Concerning the cell phone application the result should not only immediately be available from a taken photo, but should also provide a quick possibility of comparison as well. This will be achieved by access to a set of results for iconic buildings as reference. The idea is to display three references taken from the data set with values closest to the calculated one. This gives the possibility of a visual classification of the considered building.

In contrast, if the result is examined in isolation, we nevertheless see a possibility of analysation. This time the information about the changing thickness of the covering greyscale blanket may serve as characterization. Thickness strongly or hardly changes from one iteration to the next (iteration terms the calculation procedure for a certain grid size). Areas that display the most significant change are then highlighted by color.

7. Outlook

Although the application shows promising results, there are still some points which must be taken into consideration. First of all, since the object of focus is a building, it is to be questioned whether or not solely this object should be considered; i.e. whether or not the building should be extracted from its surrounding (the sky with clouds, trees and adjoining buildings). In the current state we forego the implementation of an appropriate algorithm, not least because of time performance and usability, but also because a building in real life is never looked at without its environment (including foreground and background).

Further studies also relate to the handling of influences. E.g. in order to reduce quantization effects and to improve accuracy the starting position of the grid may be changed (Lorenz 2012). Again computation time is the reason why this is not implemented yet. One additional aspect in this context is the discussion about the outcome with respect to accuracy. Therefore statistic values such as standard deviation should be included in the application.

Another focus of future work will be laid on additional applications. Two immediate proposed implementations concern a variation of the threshold segmentation and an improved differential box-counting method for colour images (Nayak & Mishra 2016). Currently threshold segmentation uses ranges from zero to a certain upper limit. However, segmentation of thresholds can also range from one limit to another: e.g. 0-12.5%, 12.5-25%, 25-37.5% and so on. This will strengthen the attention on changes of characteristics between separate ranges of grey intensities. Since colour plays an important role in perception, the improved differential box-counting method will take this part into account. In the current stage colour is only included in form of different intensity.

8. Conclusion

The here presented web application offer two fast solutions to estimate the fractal dimension of photographs taken with a mobile phone. The first one is based on the standard box-count for binary images (using threshold conversion), while the second one is based on the differential box-count algorithm applied to greyscale images. Accuracy has been tested on deterministic fractals with known fractal dimensions. It has been demonstrated that not only results (box-counting dimensions D_B) are close to the expected ones (self-similar dimensions D_s) but also that the application is a rapid and effective implementation. For test purposes the current version of the webpage is available under: www.iemar.tuwien.ac.at/processviz/fracam/ (Wurzer & Lorenz 2016).

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EFFICACY OF LOCALIZATION THROUGH MAGNETS EMBEDDED IN INFRASTRUCTURE

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Abstract. This paper investigates localization and guidance systems as important future considerations for autonomous mobility within the built environment. Specifically, it looks at embedding magnets within building construction assemblies, using magnetic sensors for autonomous navigation, and understanding the impact construction materials may have on magnetic-field-based localization and guidance systems of autonomous agents.

Keywords. Autonomous Car; Localization; Infrastructure; Robotics.

1. Introduction

The developments in personal and autonomous mobility unavoidably raise the question of the interface between the built environment (buildings, cities, and infrastructure) and autonomous agents (cars, drones, house robots, or assisted wheelchairs). This interface needs to consider and accommodate new players without an adverse impact on current users. This inclusive, yet well-tuned, integration will be critical in a successful transition from the current inert habitation to future autonomously empowered habitation. While the focus of these transformations may seem to be machine based, accommodating various forms of autonomous mobility, ultimately it will lead into more inclusive environments that will empower human users, particularly the elderly, children, and people with mobility impairments (Cowan et al. 2012; Madarasz et al. 1986).

The need for the seamless integration of new and old users may suggest a particular approach to development of autonomous-mobility-friendly environments that focus on redefinition of materiality and placement of strategic micro-gestures (embedded capabilities) without an overall typological rethinking of what is expected from buildings today. This attitude could form the first step in making buildings and cities ready for an effective integration of autonomous agents. It would also help in defining a strategy for a transition toward autonomous mobility.

This paper considers localization and guidance systems as important future considerations for autonomous mobility within built environment. Specifically, it

looks at embedding magnets within building construction assemblies, using magnetic sensors for autonomous navigation, and understanding the impact construction materials may have on magnetic-field-based localization and guidance of autonomous agents.

Numerous methods for localizing autonomous robots (including cars) have been studied for decades (Borenstein et al. 1996). In many cases, technology such as GPS can guide both human and robot drivers, with small adaptations either to be calculated by the robot or visualized for the human. Built-in technology such as road infrastructure provides an implicit layer for humans to interpret. Complications arise in decision-making, particularly in relation to other vehicles, but also in unknown circumstances. While a painted line across a stop sign can be interpreted by a person as graffiti, the difference from an untouched sign makes it difficult for image recognition. These variations create difficulty in localization for robots, and as such require multiple strategies and approaches to effectively navigate the environment. If any technology could be provided at a higher rate of reliability and consistency, the reliance on other technologies could be reduced. In the case of GPS, the satellite must be visible, eliminating tunnels; RGB cameras require lighting to detect elements; and laser scanning can have interference with reflective and transparent materials. If the infrastructure allowed for the technology to offset these challenges, the rate of adoption would greatly increase.

Indoor environments also provide ample examples of hallways with glass corridors or open doors; of glazed ceramic or stone wall coverings; and of free-form designed and undulated surfaces with posters, flyers, and unattended objects that could significantly affect the autonomous agent's ability to use computer vision and to navigate. Just as with the changing car scene on roads, anything from people to wheelchairs to dogs can populate an indoor environment. Between stands for posters, conversations around a coffee shop, and people passing by, the recording and comparison of image data can be nearly useless. The ability for a "ground truth" localization method would allow for the guaranteed path center, while supplementary data from Light Detection and Ranging (LiDAR) devices or RGB videos and could offer collision avoidance.

2. Background

Induction through a metal coil embedded in the road has been used for a long time to study traffic patterns. The induction loop is able to detect when a large ferrous metal object is near. When multiple loops are implemented in the road, timings for cars to pass over can be calculated. These induction loops can be used for traffic signals to detect when vehicles are present and trigger various traffic controls. Furthermore, these induction sensors can be fine-tuned to distinguish between various vehicle categories, such as cars, vans, trucks, and buses (Sun et al. 2003). This removes the need for image sensing of vehicles, which can be less reliable depending on light and atmospheric conditions, while improving on the basic timed system.

The reverse use of this technology would allow vehicles to detect their location within a road or a relationship to various obstacles and infrastructure elements. By

decreasing the size and increasing the spacing, accurate location information for the road can be detected. More specifically, the knowledge that these devices are centered in the road can provide a reliable and trustworthy localizing information source to the robot (or car). The same induction technologies are used, for example, as an "invisible fence" to control boundary conditions for house animals and as household robotic devices such as autonomous lawn mowers.

Induction loops could be designed to provide unique characteristics, as is the case with Radio-Frequency IDentification (RFID) technology that allows for short- to mid-range distance detection. However, RFIDs can be used to track general inventories (presence) with long-range implementations or specific locations with short-range implementations.

While there is ample (1) research and implementation of using magnetic field and sensors for autonomous guidance systems and (2) research into shielding magnetic fields and how various materials contribute to it (Shi et al. 1995; Sumner et al. 1987; Graham and Cullity 2009), little research has been done on materials specific to construction and architecture with an integration of magnets into construction assemblies as a base for autonomous localization and guidance.

The research on material shielding in physics and material sciences may not always be fully applicable to architecture and construction. Construction, especially executed on-site, introduces a high level of imprecision and usually requires a high tolerance for errors as compared to other manufacturing technologies and sciences. Materials used are often produced locally and may vary in their ferrous metal contents from similar materials elsewhere. This means that uniformity and measured outcomes may have a broad range of variations.

Construction assemblies such as floors or walls are hardly ever composed of a single material. For example, concrete slabs are made of a single or double pour with a top coating providing a finished surface. In the case of a single pour, the top of the concrete slab is often covered with carpet, wood, or tiles, usually set in with a thin set or an adhesive. Within the slab, depending on the desired structural performance, properties, and construction technology, there may be additional metal deck panning, reinforcement steel bars (rods), or metal wire mesh to reinforce concrete top surfaces against point loads. In addition to structural steel, floor slabs may also integrate a number of other elements, such as cable conduits or piping for radiant heating.

For the reason of its complexity, it is desirable to develop mock-ups for various types of floor slab assemblies and test them as composites. The case studies below show magnetic shielding tests of individual materials such as floor tiles, wood composites, and carpets as well as thin concrete slabs with various types of metal mesh reinforcements. These mock-ups were used to set up parameters and constraints necessary for the magnetic-field-based localization and guidance case study.

3. Methodology

In order to correlate the magnetic field to the material interference, base measurements of the magnet were performed. Following this, numerous measurements

with different materials and locations of the testing unit were done. Milliteslas were the units used in the experiments, while the values received from the sensors mounted on the robot were analog values between 48 and 4048.

3.1. EQUIPMENT

To test the magnetic field, a Kanetec TM-601 tesla meter was used, with a resolution of 0.1 milliteslas. For repeatability across magnets and materials, an X-carve CNC machine was fitted with a custom holder in the ER-11 collet to maintain the position of the TM-601 sensor (figure 1). The machine was controlled through the software to specify exact height distances from the testing materials.

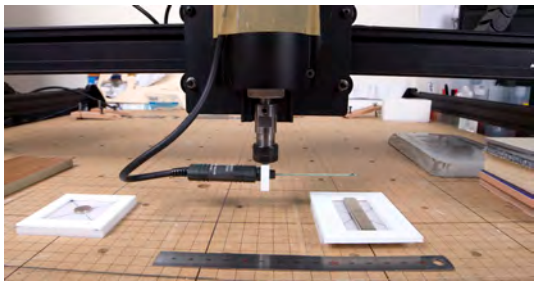


Figure 1. Testing device mounted to the ER-11 Collet of a CNC machine. The bar magnet is raised and secured via POM plastic.

Implementation of the localization was done using magnets, with a KUKA youBot and custom magnetic sensor array. Importantly, the robot had mecanum wheels, allowing for full directionality of movement. An aluminium box containing 30 AD22151 hall sensors was mounted to the rear of the robot (figure 2). The sensors were connected to an Arduino board, which connected to the computer in the robot base, transmitting serial information through USB. Data values representing the magnetic field were between 48 and 4048, corresponding to south and north poles, respectively. The base was controlled through a Python 2.7 interface with ROS, and the sensor was read using pySerial. The program on the robot was started and stopped over an Ethernet connection. While in practice this would be a wireless connection, reliability of stopping and ease of programming required a tether connection in these experiments.

3.2. DISTANCE

Multiple distances between the sensor and magnet were tested to understand the falloff of the magnetic field, and whether any materials interfered with this falloff. Base measurements of the magnet only were done at 0, 5, 10, 20, 30, 40, and 50 mm distances (vertical). Measurements with materials separating the testing device and the material were done at the same distances, provided the material height allowed. For example, a tile 8 mm thick would allow for samples 10 mm and further from the magnet.



Figure 2. The KUKA Youbot used for the experiment. The four wheels allow for omni directional movement. The magnetic field sensors are mounted in the rear of the robot and connect to the USB port of the robot.

3.3. MATERIALS

While many materials do not contain ferro-metallic particles that could affect magnetic field/flux, various construction materials were used to validate the insignificant effects such materials have. Materials used for testing included (1) ceramic tiles, 100 x 100 mm, 8 mm thick, with cobalt and white glazing; (2) pine wood planks, 20 mm thick; (3) floor carpet with non-cut loop, 6 mm thick; (4) marble stone tile, 10 mm thick; (5) vinyl flooring tiles, 3 mm thick; and (6) concrete mix. The concrete used had a manufacturer statement that the mixture contained approximately 20% sand, with a recommended ratio of 0.14 ml/g.

As concrete is often poured with rebar or metal mesh, additional material combinations were created. A steel reinforcement mesh with a 3 mm diameter in a 100 mm square was used to test top surface reinforcement used in many concrete slabs, while a 3.5 mm x 6.5 mm diamond mesh of 0.5 mm thickness was used to test concrete mesh pouring. Last, a concrete slab 18 mm thick (seen in figure 2) was poured containing magnets at the bottom for use in the centering experiments.

3.4. DIRECTIONALITY

Two tests were performed to demonstrate the ability of the robot to localize based on magnets. The first test was a sideways movement using the omnidirectional wheels to locate the robot center to the magnet. Second, magnets were placed at various distances apart to allow the robot to move forward and stop when a new magnet was found, centering upon that magnet and then continuing.

4. Results

Two main results are presented. First, the relationship between magnetic fields and location of the sensor demonstrates the feasibility as well as the difficulty of integrating magnets in the construction process. Second, the implementation of a centering robot based on embedded magnets is demonstrated.

4.1. MATERIAL INTERFERENCE

As suspected, materials showed no significant variation in interference of the magnetic field. While it is possible these materials can interfere with electromagnetic fields, as seen in some cases of concrete (Shi and Chung 1995), the concrete used in the present experiments did not show any interference. However, there was significant interference of the magnetic field when metal was introduced. The values measured from the magnet varied depending on the location. Figure 3 shows that the difference between the edge and center of the bar magnet had significant differences when tested close to the surface, but became similar as the measurement device moved further away.

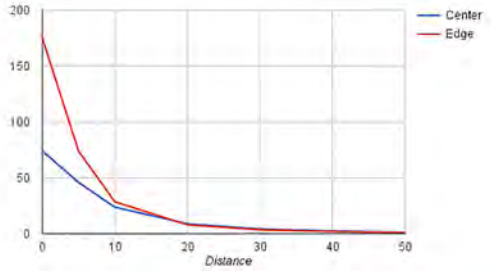


Figure 3. Base measurements of the bar magnet tested at the edge and center.

When using the wire mesh with a cast of concrete, the measurements showed a significant decrease depending on the location of the mesh. However, the effect of measuring 10 mm higher from the magnet caused a larger difference than the introduction of wire mesh. The wire mesh closest to the magnet showed the most significant difference in the magnetic field, especially at the center. When a wire mesh was introduced closest to the surface, a 26% reduction in the measured magnetic field occurred, whereby the difference between 20 mm and 30 mm reduced the magnetic field strength by 52% (figure 4).

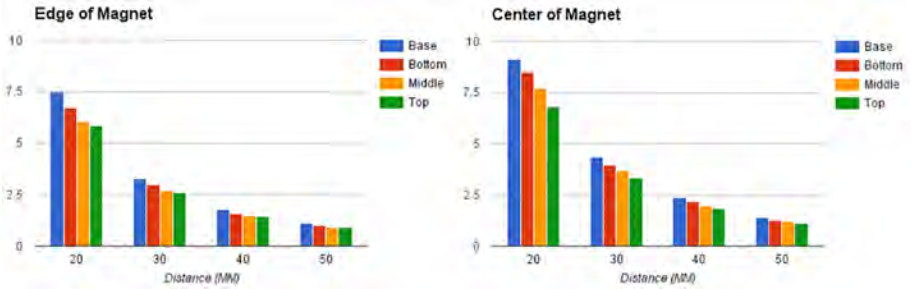


Figure 4. Left: Measurements from the center of the bar magnet. Right: Measurements from the edge of the magnet. Base is the measurement with no concrete or mesh. Bottom represents the mesh facing closest to the magnet with the concrete above. Middle is the mesh embedded in the middle of the concrete. Top is the wire mesh above the concrete. All data is based on the average of 3 separate measurements. .

Further illustrating the results showing that the distance of metal mesh from the magnet has a significant impact, additional measurements demonstrated the various distances and their effects on magnetic strength. In the case of a 5.5 mm gap between the magnet and mesh at 10 mm, the measured magnetic field decreased to 60% of the original base measurement. Comparatively, placing the mesh directly on the magnet resulted in a measured field decreasing to 96% of the original base measurement (figure 5).

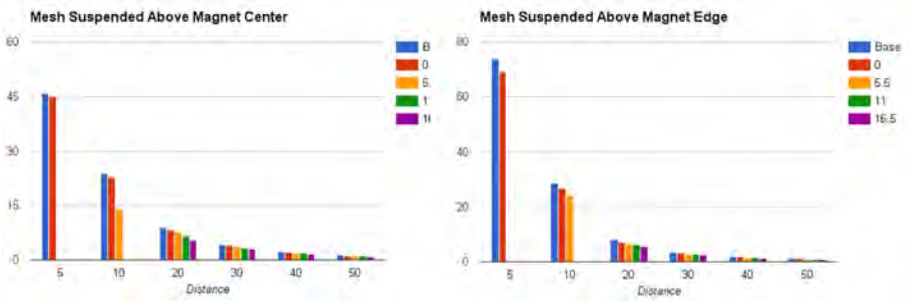


Figure 5. Various distances of the mesh from the magnet and the corresponding measured magnetic field.

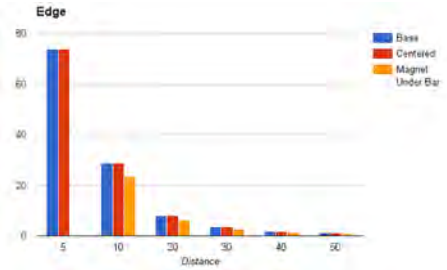


Figure 6. Results of the 3mm bar square being placed with the magnet in the center and magnet under the bar. .

The final testing was done with the 3 mm metal bar. Notably, the spacing used between bars was wide enough to have no impact when the magnet was centered (figure 6). However, placement of the bar directly over the magnet did have an impact on the measured field. As metals often used in construction are magnetic, special care must be taken to avoid the magnet attaching to the bar.

4.2. ROBOTIC LOCALIZATION

To clearly demonstrate the efficacy of using magnets for centering the robot, figure 7 shows a magnet being moved, with a real-time calculation of the new magnet location and the movement required to align to it. The process was repeatable and reliable, demonstrating the efficacy of the process.



Figure 7. Centering algorithm of the robot being demonstrated. Top Left: Robot is centered on the magnet embedded in the concrete. Top Right, an additional magnet with higher force than the embedded one forces the robot to move sideways. Bottom Left and Right: Robot autonomously centers again in respect to the embedded magnet.

The second test performed was to have the robot autonomously center on a magnet, after which it was intended to move straight forward until another magnet was found, and repeat the process. Figure 8 shows the experimental setup in which magnets were placed at random distances apart. The robot was then placed with the sensor near the first magnet to begin localization.

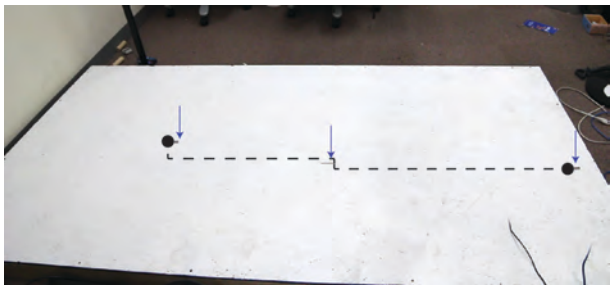


Figure 8. Three magnets were placed on the wooden platform various distances apart and with slight offsets.

The robot was able to successfully center and track until the following magnets were found. Figure 9 shows an overlay for the video. Notably, the double images of the robot at similar positions show the ability to center on the unevenly placed magnets along the path. The largest obstacle in this implementation is the spacing between magnets. As the distance increases, the error for the center of the robot increases. When this error is too high, the robot can pass the magnet without the sensor passing over it. To address this problem, additional attention to the magnet spacing is required. Another success of this experiment is seen in the free-standing magnets on the platform. While ideally the magnets are embedded into the infrastructure, the robot was able to pass over the magnets without the magnet attaching to the steel base. This demonstrates that the strength of the magnet can be low enough to have little force on metal objects while still being readable by a dedicated sensor.

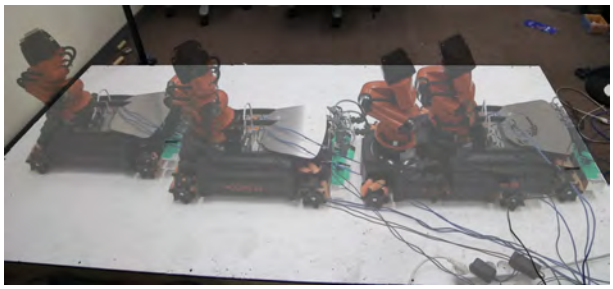


Figure 9. Overlays of the video in which the robot centers on a magnet, continues forward until another magnet is found, centers again, and continues forward until the third magnet is found, centering and ending the program.

5. Conclusion

The results presented here provide key guidelines for magnetic line following integrated into a construction site. Furthermore, the efficacy of a robot relying on magnets for basic localization, such as centering on a line, has been shown to be simple and easy to implement. When designing to integrate magnets for this purpose, the most important consideration is the distance between the magnet and the aboveground sensor. A second consideration is that the peak of the magnetic field varies across a typical bar magnet when measured at various heights. This is compounded by the introduction of magnetic shielding material, such as metal mesh or metal bars. The elimination of these materials is the best option, but if they must be used between the magnet and the floor surface, effort should be taken to reduce the distance between the magnet and the shielding material, as the amount of shielding increases when the gap increases.

Furthermore, the strength of the natural magnets greatly outweighs the strength of the Earth's electromagnetic fields by several magnitudes. The strength of the Earth's electromagnetic field is in the range of 25 to 65 microteslas, while the smallest measurement we considered in navigation was in tens of milliteslas. Demonstrating the ability to strongly detect these magnets, the sensor used in this study was able to detect the magnets lying free under the robot, while the chassis of the robot was high enough not to attract the magnet onto itself. As other research has pointed out, various materials and aggregates in concrete play an important role in electromagnetic shielding. The ability for the system demonstrated in this paper to work likely hinges on the strength of the natural magnets and the lack of high-powered electromagnets or high sensitivity to electromagnetic fields. When dealing with all magnetic fields at a high resolution, the Earth itself will create interference. However, as shown here, this level of noise is insignificant for this type of robotic navigation. Finally, the method and algorithm implemented is also sensitive enough to track a magnet under concrete while simultaneously able to be overcome by a magnet placed by hand on top of the concrete.

6. Future

The main goal of this paper has been to show that through infrastructure, the pace at which society can adopt autonomous robotics that can navigate through space can significantly increase. While magnets themselves are not an end-all solution to navigation, with little work they have been shown to aid in the centering and localization of a wheeled robot. This concept could be expanded to electromagnets as well. In this type of situation, data could be communicated to the robot as well, through various methods. For example, simple on-off commands similar to Morse code could be deciphered by the robot reading the magnet. This could provide navigation information to various robots, or act as an embedded traffic system that only robots can detect, not interfering with humans within the space. However, the benefits of using natural earth magnets may be lost, and further research is required.

Acknowledgments

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SPATIAL-TEMPORAL BEHAVIOR ANALYSIS USING BIG DATA ACQUIRED BY WI-FI INDOOR POSITIONING SYSTEM

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Abstract. Understanding of people's spatial behavior is fundamental to architectural and urban design. However, traditional investigation methods applied in environmental behavior studies is highly limited regarding the amount of samples and regions it covers, which is not sufficient for the exploration of complex dynamic human behaviors and social activities in architectural space. Only recently the developments in indoor positioning system (IPS) and big data analysis technique have made it possible to conduct a full-time, full-coverage study on human environmental behavior. Among the variety IPS systems, the Wi-Fi IPS system is increasingly widely used because it is easy to be applied with acceptable cost. In this paper, we analyzed a 60-days anonymized data set, collected by a Wi-Fi IPS system with 110 Wi-Fi access points. The analysis revealed interesting patterns on people's behavior besides temporal spatial distribution, ranging from the cyclical fluctuation in human flow to behavioral patterns of sub-regions, some of which are not easy to be identified and interpreted by the traditional field observation. Through this case study, behavioral data from IPS system has exhibited great potential in bringing about profound changes in the study of environmental behavior.

Keywords. Environmental behavior study; Wi-Fi; indoor positioning system; big data; spatial temporal behavior; ski resort.

1. Introduction

Understanding the complex interaction between environmental factors and human behaviors - or the study of environmental behavior - is fundamental to architectural and urban design.

However, the traditional research methods to collect information on human behaviors and spatial cognition have not advanced much over the past few decades.

In spite of many drawbacks, for many years researchers have relied on on-site observations, questionnaires, interviews, cognitive maps and few other standard methods. On-site observations are often challenging in avoiding the subjective bias and observer effect, apart from requiring enormous work of the investigators; questionnaires or interviews, though cheaper, are not ideal in covering detailed information of human activities quantitatively. Nowadays, the developments of indoor positioning system (IPS) and big data analysis technique, including the storage, analysis, clustering and visualization of enormous data, have provided brand new possibilities for spatial environmental behavior research, especially for a large crowd of people in complex built environments.

Based on the huge amount of spatial and temporal behavioral data collected by IPS technology, the main focus of this paper is to explore the hidden information that could be valuable in understanding how large crowd of people are occupying space, interacting in space, and redefining space. Big data analysis technique is employed to reproduce "reality" and to reveal the implicit rules.

2. Previous Research

There are many technologies that can be used in IPS, but most methods have their own deficiencies. GPS tracking technology (Nirjon et al. 2014) or antenna signal tracking (Gonzalez et al. 2008) cannot be used inside buildings because of the limitation in positioning accuracy. Radio frequency identification (Ni et al. 2003) or ultra wideband (Gezici et al. 2005) require the subjects to wear specific devices which leads to the limitation on the number of subjects and the observer effects, whereas video-based image recognition technology (Krumm et al. 2000) is costly if accurate locating is demanded. Bluetooth IPS (Feldmann et al. 2003; Rida et al. 2015) works well, but most people are not accustomed to keep the Bluetooth of their mobile phone open, resulting in possible sampling bias. Therefore, the Wi-Fi positioning technology (Cypriani et al. 2009; Rekimoto et al. 2007; He and Chan 2016) is chosen due to its balance between applicability and accuracy. Wi-Fi is the most widely-used wireless network technology in network access of mobile phone. According to the IEEE 802.11 protocol, the Wi-Fi monitor is able to record activities of the mobile device unobtrusively as long as its Wi-Fi is turned on (Liu et al. 2007). In this way, we could collect an amount of long-term, full-coverage information without observer effect, which is essential for further data analysis.

On the other hand, environmental behavior research based on IPS has made a lot of progress recently. In terms of Bluetooth IPS, Yuji Yoshimura (2014) in the Louvre Museum successfully revealed behavior patterns of visitors by using the Bluetooth positioning system. Furthermore, Vedran Sekara and his partners (2016) revealed a dynamic structure of social networks in a campus, through a mobile Bluetooth application which can search for people around. In the use of Wi-Fi information, Zhang Jin's group used the Channel State Information (CSI) time series of Wi-Fi (2016) to realize human identification. On the city scale, Piotr Sapiezynski and his partners (2015) succeeded in tracking human mobility using Wi-Fi signals. All of these precedent researches provide the reference for the research of this paper.

3. Wi-Fi Indoor Position System

The Wi-Fi IPS is widely used to track people in public space (Yeh et al. 2009), commercial space (Zeng et al. 2015) and urban space (Sapiezynski et al. 2015). The system works as follows: A Wi-Fi enabled device broadcasts signal to the surrounding access point (AP) at a timed interval, which depends on the setting and working condition of the device. When the device moves into the detectable area, the monitoring AP will record the signal information consist of time, media access control (MAC) address of device and received signal strength. There are multiple APs recording signals of the same device at the same time. Based on the relationship between the received signal strength and the distance to the signal source, we may locate the device through the algorithm of trilateral positioning (Zhu & Feng 2013), which is a geometric positioning algorithm based on the distance between points. In addition, a pre-measured fingerprint field (Mok & Retscher 2007) may contribute in improving the positioning accuracy.

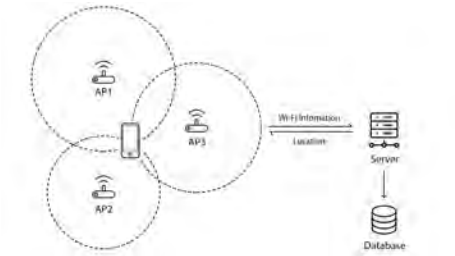


Figure 1. The basic model of Wi-Fi Indoor Position System.

In general, it is possible for a well-planned network of APs to record the spatial-temporal locations of people (mobile devices to be exactly) in certain architectural space. Once identified by the MAC address, the data can distinguish the type of devices, depict the behavioral trajectory of people, and provide abundant and valuable information in environmental behavioral studies. After eliminating device noise by filtering mac addresses, active time and active range, the Wi-Fi positioning data is ready for use in the further behavior analysis of the next phase, which will be introduced in the case study in Vanke Songhua Lake Resort.

4. Case Study in Vanke Songhua Lake Resort

Vanke Songhua Lake Resort is a newly opened ski resort located in Jilin City, northeast of China. There is a 250-meters-long commercial pedestrian street in the central town of the resort, providing ski rental, catering, family hotels, etc. We were commissioned to analyze the human behaviors in the pedestrian street, using a data set of 200 million anonymous Wi-Fi IPS records from January to March, 2015.

A family hotel, including a restaurant providing breakfast is located in the north part of the pedestrian street, while many restaurants in the middle part, and ski rental area in the south part with the ticket office. The mountain and ski slopes located further south. Ski slopes open from 8:00 to 17:00 during the day, and

night skiing is between 18:00 and 21:00. Most shops are open until 21:00.

The dataset covers 60 days and captures 1607171 unique locations from 466065 different MAC addresses after compression. Table 1 shows some examples of raw data.

Table 1. Examples of collected data.

Time	Mac Address of Device	X coordinate	Y coordinate	Mac Address of AP
2015-1-31 12:29:48	D4970BB0**3E	2220000	2123000	70BAEFAF32D0
2015-1-31 12:29:48	D857EFC9**9A	2221000	2135000	70BAEFAF4A80
2015-1-31 12:29:48	E0191DBA**11	2072000	2837000	70BAEFAF4AF0
2015-1-31 12:29:48	EC852F52**7D	2806000	3496000	70BAEFAF4790
2015-1-31 12:29:48	00082236**FB	2696000	3075000	70BAEFD98200

In addition to the Wi-Fi IPS data, we also obtained a set of anonymous data as the baseline reference, including the number of ticket sales, the number of ski rentals, ropeway card records, and mobile phone attribution information. As a study of environment behavior, our research is mainly carried out on the Wi-Fi IPS data.

4.1. DATA DISTRIBUTION

Through the accumulation of 60 day's data, we manage to form a general view of the spatial distribution of people in the pedestrian street, as well as the temporal distribution of skiers' amount, in a weekly cycle.

Figure 2 shows the accumulative distribution of data in 60 days, which allows us to have a preliminary understanding on the Wi-Fi system coverage and the spatial distribution of people. It can be observed that people are mainly distributed along the pedestrian street. The darker color of areas are important functional spaces such as hotels, restaurants and ski rental shops. Because of the limitation of the trilateration algorithm, the device is positioned at nearest AP when the Wi-Fi signal is unstable, making the locations of AP the darkest points. The right part of the figure is a hotel whose Wi-Fi system is a separated system, so it is beyond the coverage of our data.

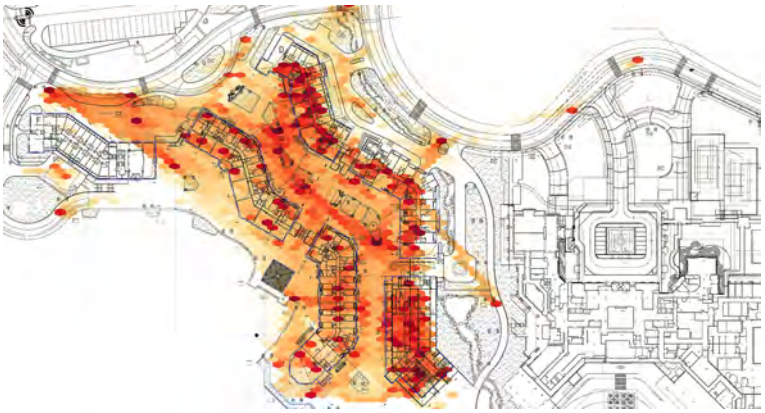


Figure 2. The spatial distribution of data.

On the other hand, the daily flow of skier's devices is counted and plotted in figure 3. It could be calculated that the flow is about 34% larger in weekends and 15% larger during the Spring Festival holidays on average, which is consistent with the common understanding of the features of a sport resort. The first day of holiday is the Spring Festival's Eve, the day of family reunion, which resulted in the smallest flow of skier's devices. Then the flow first increased then decreased during the Spring Festival holidays. Due to the holiday, the two flow of neighboring weekends have been suppressed, and are lower than other week ends.

The polyline on the graph represent the number of people using the ropeway. It can be calculated that the correlation between the number of ropeway record and the number of devices is 0.9137. Though the devices do not exactly have one to one correspondence with people, the number of devices is still never the less a reliable reflection of the resort's traffic.

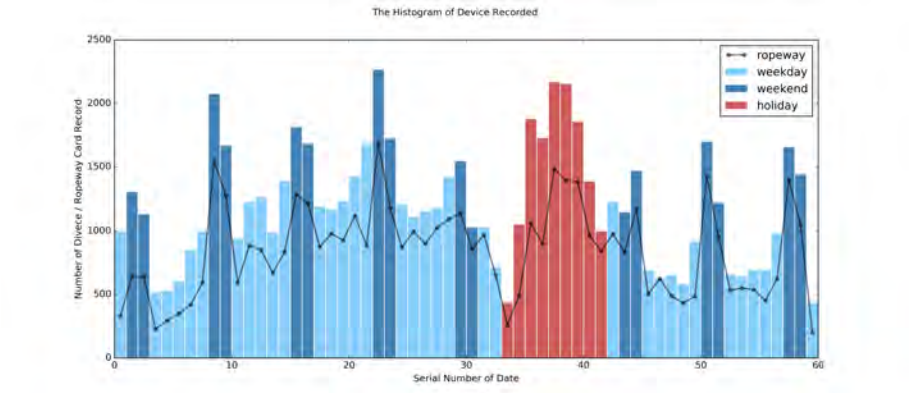


Figure 3. The number of devices recorded, during 16-01-15 to 16-03-15.

4.2. SUB - GROUP ANALYSIS

In addition to the simple description of population distribution, Several typical big data analysis methods like the k-mean clustering algorithm are used to carry out the more in-depth analysis.

Data sets cover two broad categories of people, customers and staffs, and the behavior of them must be differentiated. The traditional classification method is the "one size fits all" approach, using a single indicator as a threshold. With the help of big data tools, a series of indicators could be extracted to describe each person, including the number of days of arrival, the length of stay, the spatial deviation amplitude and so on. By the k-mean clustering algorithm, we are able to classify the crowd without losing information.

We define the "arrival time" of a person in a given day as the first time that his/her MAC address is recorded, and the "departure time" is the last recorded time. All people can be plotted in the two-dimensional space formed by the arrival time and the departure time that resulted in a density map (figure 4). Since people always arrive before depart, there is no data in the lower triangle of the map. Data

points located in the upper left-hand corner (0:00 to 24:00) indicate people who stay in the resort all day.

As can be seen from figure 4, the behavior pattern of customers and staff are very different, indicating that the classification is credible. Customers arrive at around 9:00 am and leave the resort around 16:00 pm, the same as the operating hours of ski slopes. On the other hand, the arrival and departure time of staff is very concentrated, showing their working hour is quite fixed.

Further analysis of the arrival and departure time reveals additional information. The distance that a data point is away from the diagonal line from the lower-left to upper-right represents the length of period the device stays. There is a significant group of customers whose data lies between the 3-hour line and the 5-hour line. In fact, the resort offers a half-day (3 hours) skiing ticket. Hence, these customers can be inferred as those who pay for half-day ticket considering the time of renting equipment and lunch. On the other hand, it can be found that some customers are arriving around 19:00 and leaving around 21:00, who may be the night skiers.

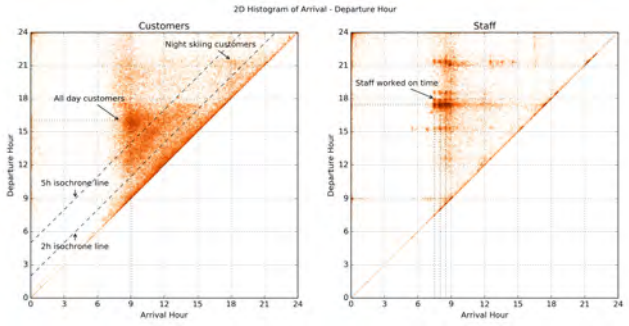


Figure 4. The arrive - departure time of different group, classified by the k-means algorithm.

The hourly spatial distribution of customers and staff are visualized in figure 5. The figure reveals that customers tend to be active during the day. As early as 7:00 - 9:00, there is a flow's peak of customers at breakfast area. Afterwards, the main crowd moved to the ticket hall and ski rental area. Lunch peak occurs mainly in 12:00 - 14:00, with heavy traffic among the entire area of the pedestrian street. Then the main customers flow back to the ski rental area. After 17:00, the closing time of the slopes, customers flow gradually decreased, but there are still some people in the area of restaurant and family hotels. And a small number of night skiing customers appear in the ski rental area.

As for the group of staff, the spatial distribution can be divided into three periods: 21:00 - 8:00, 8:00 - 17:00 and 17:00 - 21:00. Indicating that staffs generally have a fixed position and working hours. The spatial distribution can be explained by the resort management.

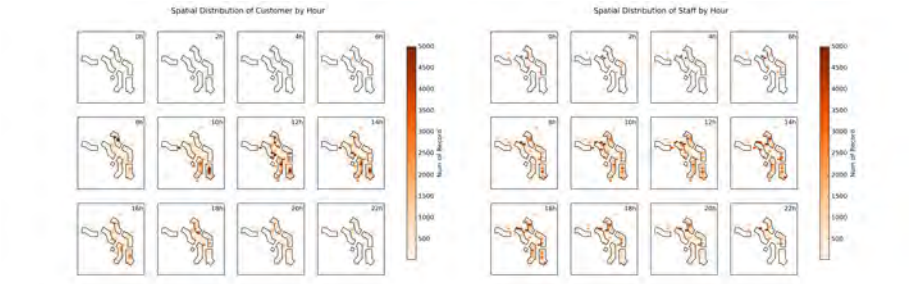


Figure 5. (Left) Spatial distribution of customers by hour; (Right) Spatial distribution of staff by hour; Solid lines represent the building.

The analysis above indicates that, data set collected by Wi-Fi IPS can not only reveal the general environment behavioral patterns of people, but also be used in classifying people and revealing the behavioral pattern of each sub - group.

4.3. SUB - REGIONS ANALYSIS

The APs in the resort cover the major shops and public spaces in the pedestrian street, thus we can analyze the traffic in different areas and find different customer behavior patterns for types of public spaces or shops. Figure 6 is the hourly traffic map, showing different characteristics of different shops.

Ski rental shops have a relatively uniform flow during daytime, with a small peak in early 9-10 am. For the restaurants, fast - food restaurants have large traffic concentrated in the lunch time, while Chinese restaurants present 2 peak in lunch & dinner time. Family hotel restaurant has a significant peak in breakfast time. Peak flow of ticket office emerges at 9-10, and then maintain a certain amount of traffic.

Meanwhile, Apple user and non-Apple users can be distinguished by the MAC address of the devices, so it is possible to make comparison of these two group of people. For example, compared to ordinary restaurants, the ratio of Apple users in the coffee shop is 15.87% higher than the average. This may imply to the different consumption habits of different groups of people.

Examining the arrival and departure time distribution in different spatial regions (figure 7) may reveal the impact of different spatial functions on people's behavior. For ski rental shops, customers may go to the shop many times for renting and returning equipment. All-day skiers and half-day skiers can also be distinguished in the ski rental shop. For restaurants, customers will stay longer in Chinese restaurant during lunch and dinner, while fast - food restaurants may experience a greater peak in lunch, with shorter staying time. As for the ticket office, the full-day skiers and half-day skiers can be distinguished on the distribution graph. Since the customer need to return to the ticket office to get their deposit back.

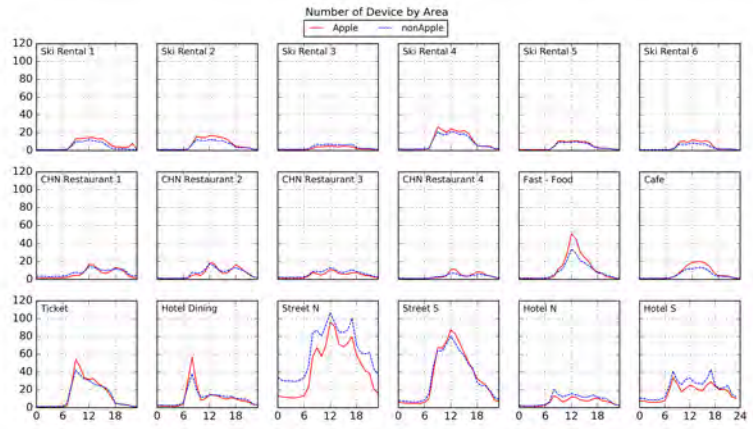


Figure 6. Hourly traffic for different shops, blue for Apple users.

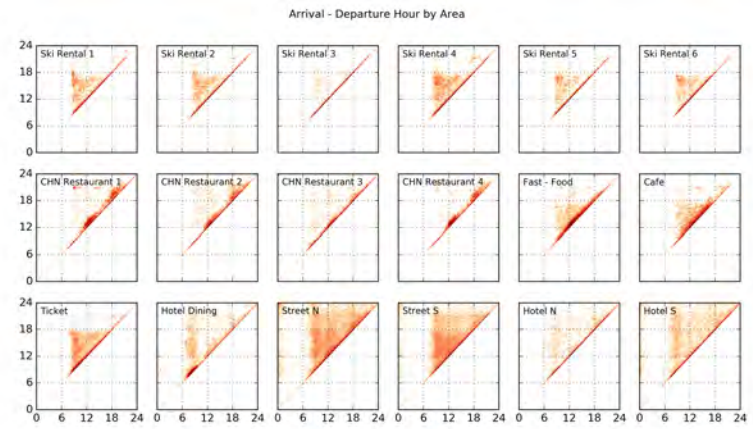


Figure 7. The arrival and departure time in different shops.

5. Discussion

The architectural space and individuals inside the space together compose a complex system, especially for large public facilities with big flow of people. Revealing people's behavior pattern in such complex system has great value for design, management and daily life. Contemporary IPS technologies and big data analysis methods have greatly extended our ability in understanding people's spatial behavior. Comparing to traditional environmental behavior investigation methods, IPS system is capable of fully covering the entire investigating area, working continuously for many days, and collecting data of large amount of people. Its advantage lies in that, firstly, since the data has full spatial and temporal extension, so from

the angel of individuals, it can depicture the whole spatial-temporal trace of individuals, and from architectural angle, it can reveal the spatial function network and its evolution; secondly, since the data contains trajectory information for huge amount of people, it has potential of revealing different patterns and variations of behavior in the space; thirdly, if we consider the multitude information in different dimensions such as time, space and different group of people, there could be more in depth analysis regarding people's behavior pattern.

In this paper, based on the 60 days Wi-Fi IPS data of a ski resort, we firstly try to depict the general spatial and temporal pattern of people's flow, and then explore more in detail the behaviors for different groups of people and in different areas. Clustering algorithm is used in dividing customer and staff, and its result is validated by temporal analysis of arrival-departure time. Furthermore, daily flow of customer in different area and shops are compared, revealing that function has great influence in people's activities. These analyses demonstrated that Wi-Fi IPS data contains abundant information of behavior, and could become a good source for environmental behavior research.

It should be pointed out that although IPS big data contains abundant information of a large number of people, it could still be biased. The data set may be contaminated by noise from other devices in the environment, and there may be the systematic deviation in the process of using mobile devices to represent people, including unopened Wi-Fi, non-smart phone, carrying multiple devices and other possible situations. Furthermore, IPS data does not contain information of behavior type, and we can only infer it by the location. It is even harder to know what people feel and think, which may have to be inferred by other data source such as social media data. In many situations, on-site observation and interview are still very important. Though the samples are limited, they still give us an alternative in-depth insight.

Further researches could be carried out using machine learning algorithm, which may help us descending dimension and extract underlying patterns. Multiple data sources could also be taken into account in analysis to construct a more complete description of environmental behavior. Although the process of converting from research results to concrete architectural design still relies on the architect's experience, wisdom and creativity, the algorithm based on these abundant data will promote the further development of generative design in the future.

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Digital Fabrication

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PROJECTABLES

Augmented CNC Tools for Sustainable Creative Practices

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Abstract. CNC cutting machines have become essential tools for designers and architects enabling rapid prototyping, model-building and production of high quality components. Designers often cut from new materials, discarding the irregularly shaped remains. We introduce ProjecTables, a visual augmented reality system for interactive packing of model parts onto sheet materials. ProjecTables enables designers to (re)use scrap materials for CNC cutting that would have been previously thrown away, at the same time supporting aesthetic choices related to wood grain, avoiding surface blemishes, and other relevant material properties. We conducted evaluations of ProjecTables with design students from Aarhus School of Architecture, demonstrating that participants could quickly and easily place and orient model parts reducing material waste. Contextual interviews and ideation sessions led to a deeper understanding of current work practices and sustainability issues with CNC cutting-machines, and identified useful features for interactive packing to reduce waste while supporting aesthetic concerns for exhibition quality design projects.

Keywords. CNC cutting; sustainability; digital fabrication; visual augmentation.

1. Introduction

In recent years, digital tools have revolutionized the field of architecture from parametric modeling in CAD, form acquisition using spatial scanning, and construction of functional components in 1:1 scale using CNC fabrication machines

(Picon 2010). Large format cutting using laser, knife, and waterjet have become basic tools for model building, exploration of form, and construction of formworks. Architects are expected to demonstrate a fluency in customizing and even creating digitally enhanced tools and processes whether to develop new visual expressions or new construction methods that support goals of sustainability in the workshop (Fleischmann et al. 2016; Kolarevic 2001). Design schools and architecture studios represent a unique user group of digital fabrication tools - the individual jobs vary tremendously, the level of finish is often very high, and work practices such as rushing to meet deadlines for public exhibitions result in huge amounts of waste. The 'whatever it takes' attitude frees the designer in some ways, however, in most craft professions such as woodworking, weaving, metalworking, the conservation of expensive material is ingrained into the learning process. There is an increasing demand in the design fields to support sustainable practices (Beorkrem 2012) through the development and customization of digital fabrication tools. Including designers and architects in the design process of digital fabrication tools offers the benefit of developing sustainable solutions that fit appropriately into the existing practices and potentially reveal unmet needs (Sanders and Stappers 2008). A typical approach in architecture and design schools for learning and disseminating skills with new digital fabrication tools involves holding workshops to guide students through a project (Merritt & De Azambuja Varela 2014) with a constrained design case that incorporates learning by doing. Often the learning outcomes involve reflection on the frustrations, constraints, and idiosyncrasies of the software and hardware (Seely 2004; Varela & Merritt 2016).

We introduce ProjecTables, a visual augmented reality system for sustainable reuse of sheet materials on CNC cutting machines. The design of ProjecTables has been informed by an investigation into the current practices of design students at Aarhus School of Architecture when using CNC cutting machines. Concretely, users can interactively pack a 2D CAD model on one or more sheet materials on the work surface of the CNC machine or on a separate table away from the CNC machine. The system uses an overhead projector, which superimposes the 2D CAD model on the sheet materials, and a traditional mouse for manipulating the model. The system allows for reuse of irregularly shaped sheet materials that would previously have been thrown in the trash, reduces the idle preparation time at the CNC cutting machines by using a separate table for packing the CAD model on the materials, and supports designers in making aesthetic choices related to wood grain, avoiding surface blemishes, and other relevant material properties. Figure 1 and this short video demonstrate the system in use (Rasmussen et al. 2016). We conducted evaluations of ProjecTables with design students from Aarhus School of Architecture, demonstrating that participants were able to quickly and easily place and orient model parts on scrap materials thereby enabling reuse and reduction of material waste. Furthermore, contextual interviews and ideation sessions with these design students revealed issues with current work practices and unsustainable use of the CNC cutting-machines at the school, and identified new useful features for interactive packing to reduce waste while supporting aesthetic concerns for exhibition quality design projects.

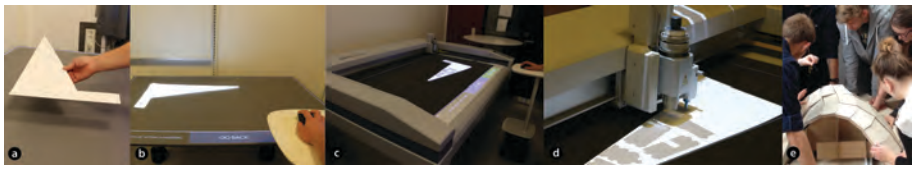


Figure 1. ProjecTables process flow: a) scrap material is found, b) designer places the scrap material on the ProjecTables preparation table to scan the contour or c) directly on the CNC cutting surface d) CAD model parts are projected on the material for position adjustment, d) model parts are cut by the CNC cutting machine, e) resulting model is built.

2. Related Work

Subtractive techniques in fabrication usually result in material waste, driving architects to explore strategies of waste reduction while maintaining high aesthetic value. In the Umwelt Arena, architects designed the interior and exterior balustrades to be produced from a single sheet material such that all parts become elements in the construction with no material waste (René Schmid 2012). While zero waste may be a design ideal, it is important that the tools remain flexible to support the variety of challenges and ways of working in design studios. The work presented in this paper builds upon recent research on digital fabrication tools, interactive fabrication that brings the designer closer to the act of fabrication, and interactive packing using visual augmentations to assist in positioning CAD model parts on fabrication materials.

There has been some exploration into closing the physical gap between the digital fabrication tools and the crafted object, bringing the designer's hand closer to the moment of fabrication. Sharing some of the aims with the framework of Direct Manipulation (Schneiderman 1983), prototypes presented as explorations in Interactive Fabrication (Willis et al. 2011) investigate opportunities for real-time input to digital fabrication tools in the creation of physical form. These prototypes place the designer in more direct interaction with shaping the material and building upon the emerging form. In order to deal with the unpredictable results of free-hand, interactive digital fabrication, Interactive Construction (Mueller et al. 2012) maintains the step-by-step design process of interactive fabrication, but introduces geometric constraints to the drawing tools enabling users to take advantage of the precision of CNC machines to construct functional mechanical devices. Olwal et al. augment a CNC machine with real-time data on occluded tools and processes using a transparent holographic optical element, overlaid onto the safety glass (Olwal et al. 2008). Saakes et al. introduce the concept of interactive 2D packing of CAD models for effective material reuse on CNC cutting machines (Saakes et al. 2013). Sakes et al. evaluate a set of interaction techniques for interactive 2D packing using a prototype, PacCAM, which consists of an overlooking camera, which captures the sheet materials on the CNC cutting bench, and a nearby screen-based interface, wherein the CAD model is visualized and manipulated on top of the sheet materials. Visually augmenting the physical surface of a sheet material with a CAD model by use of a projector has been explored in low fidelity prototypes by (Winge et al. 2014). In that research focused on designers as users,

and feedback from the users suggest that such visual augmentations can be helpful for positioning model parts for cutting and that the familiarity of the standard mouse provides a simple input modality for moving and placing model parts. The present paper extends the work on interactive 2D packing and visual augmentations of CNC machines, by exploring visual augmentations of 2D CAD models directly on sheet materials to be cut. Our aim is to support practices that are more sustainable through a reduction in material use while enabling aesthetic practices and techniques within the creative context of a school of architecture.

3. Current practices

We conducted an initial inquiry involving observations and contextual interviews at Aarhus School of Architecture, which identified three main issues that design students encounter using the CNC cutting machines at the school: 1) Reuse of scrap materials is difficult, 2) students need to make design choices based on the properties of the materials, 3) waiting to use the CNC cutting machines can involve long delays during busy periods. We address these issues in the design of ProjecTables.

3.1. MATERIAL REUSE

Observations in and around the workshop at the architecture school revealed that students usually nest their CAD model parts into a tight rectangular shape in the CAD software, and they try to place this rectangular shape of model parts as close to the edge of the sheet material as possible to optimize material use. Some students use tape to align the CNC workbench and material to ensure alignment of the rectangular shape to the material. However, when nesting on a scrap material they rarely take into account its shape and cutouts, which results in a nested rectangular shape of model parts that are placed sub-optimally, making the scrap material even more difficult to reuse after the cutting job.

Likewise, observations revealed various material scraps were thrown out including pieces with large uncut regions as shown in figure 2. Students rarely make attempts to reuse scrap material if the remaining piece is small or irregularly shaped for a variety of reasons.

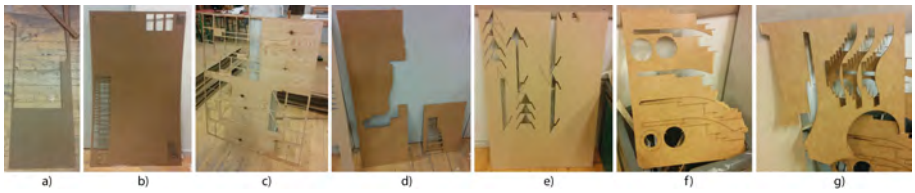


Figure 2. Scrap materials found in the workshop dumpster and waste bins at the school of architecture: a-e) large areas of uncut material with a notable tendency for cutting to take place around the edges and corners, f) & g) scrap material with difficult to use uncut regions.

Industry-standard CAM software has no knowledge of the size, shape, or appearance of the scrap material on the cutting bench, and thus the CAM software cannot provide direct visual information to the student on where to place her CAD

model within the material bounds, making reuse a difficult and time-consuming task. Also, students often make one-off models. This means that a student will buy a new piece of sheet material such as medium density fiberboard (MDF), use a portion of it for a project, and then store the rest for later in her workspace or office. However future projects may require different thicknesses and types of materials. Therefore, over the course of a school year a student will accumulate a lot of different scrap materials from different projects, until a decision is made to throw them out because they either take up too much space or are too damaged from being moved around. When students occasionally do attempt to reuse a scrap material, it is typically during project deadlines, when no new materials are available, or when the material is very expensive.

3.2. USING MATERIAL PROPERTIES AS DESIGN CONSTRAINTS

Our contextual interviews showed that the students' attention to material properties - such as smudges, holes and burned edges - is almost instinctive and that the importance of the appearance of a model depends on its design purpose. The appearance of a model used internally in the design process is not as important as the appearance of exhibition models. For instance, for a model that is going to be exhibited it matters that interlocking parts with a texture, such as wood grain, are oriented in the same direction or following a consistent strategy. Similarly, waste cardboard has been elevated to a precious material for designer lamps (Graypants 2016), which utilize alternating orientation of cardboard layers to provide an attractive play of light. For a quick and dirty model, scrap materials can be used because any small holes or burned edges in the material do not necessarily matter. Additionally, when using a wooden material, the direction of the grain on some model parts matters for a functional reason, as the strength of the parts may depend on it. For instance, a long rectangular part of veneer with the grain going in the opposite direction of its length may easily break when handled.

3.3. WAITING TO USE THE CUTTING MACHINES

During the contextual interviews, the students told us stories of how the line of users waiting to use the CNC cutting machines would sometimes close to project deadlines be so long that they would have to wait for days to get access to the machines. Students spend a large portion of the total time of a cutting job on preparing the job - placing the CAD model correctly on the material and assigning tools to the paths of the model - at the CNC cutting machine (Winge et al. 2014). During this time the machine is idle. However, if the machine could be cutting during the preparation of cutting jobs, this would reduce the line to the CNC cutting machine.

4. Design of ProjecTables

It is evident from the accounts of current practices that the way students currently manage scrap materials involves haphazard and ad hoc strategies, thus in the design of ProjecTables we address the identified issues with the mission of supporting designers toward more sustainable digital fabrication tools and practices.

The ProjecTables system consists of two main parts: the preparation table and the cutting bench of the CNC cutting machine. Each provides a planar surface where the user, the designer or design student, places sheets of materials they want to prepare for cutting.

Initially, the user prepares a CAD model for fabrication on one or more materials at the preparation table, a normally sized table dislocated physically from the CNC cutting machine. The user does so by placing materials arbitrarily on the preparation table and telling ProjecTables to capture the material contours with the overlooking camera. ProjecTables provide feedback on the capturing process by superimposing the material contours on top of the physical materials using the projector. The user then opens up a CAD model and ProjecTables superimposes the the model on the materials in 1:1 scale using the projector. The user may select, translate and rotate parts of the model to manually pack the parts within the materials, using a mouse as input device. When the user is satisfied with the placement of the model parts, she tells ProjecTables to save the material/model configuration. Thereby ProjecTables saves the position and rotation of the model parts on the materials in the cloud. The user picks up the materials from the preparation table, transitions to the CNC cutting machine and throws the materials arbitrarily on the cutting bench. She tells ProjecTables to capture the material contours using the overlooking camera. Then, ProjecTables looks for a match between the current materials on the cutting bench and previously saved materials from the preparation table. If a match is found, the position and rotation of the model parts are restored from the cloud and superimposed on the materials. The matching takes approximately 5 seconds. If the user is still satisfied with the placement of the model parts, she can confidently start the cutting process. However, if the user would like to alter the placement of one or more model parts, this is possible before cutting, again using a mouse as input to manipulate the model parts. Finally, the user starts the cutting process, and the model parts are cut out directly where they are superimposed on the materials.

The hardware of ProjecTables currently consists of one preparation table and one CNC cutting machine. The preparation table consists of a table, an overlooking projector, an overlooking camera, a computer, and a mouse for manipulating model parts. The table is coated with a dark gray matte paint suitable for projection. The CNC cutting machine is likewise rigged with an overlooking projector, an overlooking camera, a computer, and a mouse. See figure 3 (left) for a technical overview of the ProjecTables system. The software of the ProjecTables system is written in Java using the Processing framework and OpenCV. Machine code conversion of CAD model files to HP-GL commands for moving the CNC cutting head is handled by proprietary software.

5. Evaluation

In order to understand the benefits and drawbacks of the ProjecTables system and to gain input on how to design useful features for the system, we invited architecture and design students, who are frequent users of CNC cutting machines, to take part in evaluations using the prototype. This involved a mix of quantitative and qualitative measures. Ten participants took part in a quantitative evaluation test-

ing their performance in packing shapes on to scrap materials using existing CNC cutting software to gain an overall sense for completion time and cutting errors. We then conducted the same packing task and contextual interviews with four additional participants using the ProjecTables prototype to explore possible features in future iterations of the system.



Figure 3. (left) ProjecTables system overview: CNC cutting machine with overhead projector and camera connected through the internet to the preparation table, also with camera and projector for capturing material contours and displaying model parts. (right) Packing task: Participants were tasked to fit the model parts in the available pockets of space on the scrap material. Model parts are white with a red outline, holes in the material are solid black.

The 10 Participants, 1 female and 9 males with average age of 25.6 years, were asked to pack model parts onto a piece of scrap material, taking care to ensure that the parts would be cut and not overlapping with the holes or edge of the material. The challenge of the task was to find the small pockets of space in the material, where specific parts of the model would fit as shown in figure 3 (right). This is a typical task faced by designers and it typically requires careful measuring and verification of the bounds of the part fitting properly. The participants performed this task using standard CNC cutting software, which they were familiar with and had used at their institution. Completion time and number of errors were measured. The results of the packing task confirm the observations at the architecture school that the placement and cutting of individually placed model parts takes a considerable amount of time and often results in miscut parts. Individual parts took between 2 and 4 minutes to place and this time varied widely between participants (M=168.7seconds SD=33.8). Furthermore, 20% of the attempted cuts resulted in errors - placing pieces of model parts in cutout regions of the material. Performing this task using ProjecTables is up to 30x faster and is categorically different from using standard CNC cutting software, because the standard software requires the user to measure the material and jog the origin laser indicator to set the origin and then explore the bounds of the parts.

We selected 4 additional participants, who use the CNC cutting machines regularly (5-30 times per month), to go through a packing task using ProjecTables and to take part in a contextual interview. All participants spent between 1 - 3 minutes completing the packing task (8 - 26 seconds per individual model part) and made no cutting errors. During the interview we had them reflect on their current practices and problems with the CNC cutting machines at their institution and conducted ideation sessions with them to generate and discuss possible features for ProjecTables, which would be useful to them in their everyday design practice. We asked them to reflect on their interactions with ProjecTables and invited them to share feature ideas pertaining to improved packing and support of sustainable

practices. Four main ideas emerged: 1) snap-to angles for improved efficiency of packing, 2) providing a visual margin between parts to account for the sacrificial material that is cut/burned away by the tool - for instance when laser cutting thick plywood, larger burn marks appear on both sides of the cut line compared to thin plywood, 3) sharing of paths between parts to optimize material use, and 4) automatic visualizations to identify possible packing locations of model parts, thus reducing the time for manual exploration of where to fit the parts.

Additionally, we asked participants to describe how ProjecTables could support them in using material properties and visual augmentations hereof to inform and constrain their designs aesthetically and functionally, which resulted in two main ideas including 1) the selective automatic alignment of model parts according to the material grain or texture, and 2) allowing the user to choose the level of material fidelity. The latter idea would involve visually marking up areas on the material as "no-go'' zones where model parts may not be placed. Through deeper discussions, it was clear that the directionality of texture and quality of model parts is only important for the visible parts of exhibition-grade models and for models where the structural strength is crucial.

When participants were asked to compare the use of ProjecTables with current practices, 3 participants described how they believed the system to better support reuse of scrap materials than current systems at the architecture school, because they found the system to be easier and faster to use. 1 participant described that he would prefer to use the CAD program, Rhino 3D, when packing a model consisting of many small parts, as he would want to be in precise control of defining the distance between parts to save space. Participants agreed with the overall reasoning for the preparation table - they had all experienced long wait times of hours, some even days, to get access to the CNC cutting machines at the school. Moving the activity of preparing models and materials away from the CNC cutting machines to reduce the idle time of the machines thus made good sense to them. Interestingly one participant also noted how preparing a model on the preparation table, rather than on the bench of a CNC cutting machine, was more ergonomically pleasant as he could walk around the table, while preparing his material, and he could lean in over the table without worrying about security sensors going off. Thus the participant claimed to have more freedom in his actions at the preparation table than on the CNC cutting machine.

6. Discussion

Participants of the contextual interview expressed concerns that automatic tools, such as automatic nesting of CAD models on materials, impose constraints and limit control causing them to change the design in ways they do not appreciate or which does not make optimal use of the material. Thus, they wanted future automatic and intelligent tools of ProjecTables to be optional and easy to override for support creative freedom. This is reasonable considering that architectural designers working with digital tools of fabrication 'struggle for clearer control over the parametric relationships' that make up the design process (Beorkrem 2012).

ProjecTables augments the CAD model directly on the sheet materials by use of

a projector, which differs from using a screen-based visualization. The disadvantage of a screen-based interface is that certain tactile qualities of a material, such as surface irregularities, cannot always be captured and represented on a screen, whereas using ProjecTables the material can be manipulated - moved around and felt - directly on the preparation table/cutting bench with the hands. Yet, as became clear in our evaluation, some participants expressed a preference for using a screen-based interface and mouse for interactive packing. This may be due to the participants familiarity of the screen-based interface (Winge et al. 2014). It may also be due to the input from the mouse being experienced as detached from the output and the otherwise direct manipulation of the material on ProjecTables. Substituting the mouse input with touch input for manipulating the model parts, however, could complement the direct interactions with the material and make for a more coherent tangible experience where input and output is tightly coupled (Fishkin 2004). Still, we assume there are benefits and drawbacks of both approaches to visualization and thus an interesting future study would be to compare the two.

7. Conclusion and Future work

We presented ProjecTables, a visual augmented reality system for sustainable reuse of scrap sheet materials on CNC cutting machines that supports important aesthetic concerns and practices of architectural designers. In future longitudinal evaluations of the system at the architecture school we will examine how it supports the sustainable use of scrap materials in terms of quantitative reduction of material waste, reduction of idle time of the CNC cutting machine, and how the designers appropriate the system features into their work practices. We plan to develop a digital, web-based material library system to be used in combination with ProjecTables to experiment with different social models for sharing (scrap) materials between design students at the architecture school. To further drive a reduction in material waste, we are developing a smartphone version of the preparation table. This enables designers to quickly measure and determine if scrap materials, found away from the studio, are useful for their design projects. We hope that our work inspires the research community to focus on sustainability issues when developing interactive systems for fabrication, not only for the DIY and maker communities, but also engaging with the unique and important challenges encountered in architectural studios and design practice.

Acknowledgements

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A SIMPLE FABRICATION SYSTEM FOR UNFOLDING COMPLEX ARCHITECTURAL SURFACES

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Abstract. In this research, we explore the implementation of panels with a single bending direction as cylindrical surfaces; in so doing, we present our ongoing research, focusing on finding ways to simply and affordably address the problem of constructability of double-curved structures. By encoding 3D freeform surface information into a 2D workflow, our in-house software (named UNFOLDING) breaks down complex mesh structures into a number of discrete and flat quadrilaterals that can be translated into a fabrication layout. UNFOLDING provides a practical way of linking the process of production and assembly to freeform architectural design. After introducing UNFOLDING in two design studios at Texas A&M University, freshman architecture students used laser-cut quadrilateral panels to design and construct several complex forms with positive or negative Gaussian curvatures.

Keywords. Complex architectural surfaces; digital fabrication; quad-edge panels; unfolding; 2-manifold meshes.

1. Introduction

Over the past few years, the increasing use of CAD tools has made the process of designing freeform surfaces much easier for architects. Enhancing architects' capabilities to create complex forms, however, has yielded significant engineering challenges, especially with regards to finding appropriate ways of materialization (Sun et al. 2012; Brell-Cokcan et al. 2009b). This major digital design paradigm shift at play in architecture does not offer enough satisfactory alternatives to the economic constraints of the existing, well-established fabrication processes and associated materials. For instance, the use of nearly two-axis cutting technologies (such as plasma arc, laser beam, water jet, or CNC routing) is rooted in the common construction materials that come in flat panels; such materials do not stretch and are impossible to bend. As a consequence of such conventional manufacturing techniques, most curved objects that should be constructed from sheet material are

limited to developable surfaces (Pottmann et al. 2007). When attempting to fabricate a complex 3D form, one is challenged to employ production strategies that for the most part are correlated to 2D fabrication, including contouring, triangulation, and unfolding (Kolarevic 2001). Construction of very complex forms with warped, twisted, or non-developable surfaces is still expensive (Ali 2013; Pottmann et al. 2008) and complicated, as well as risky to assemble. Manufacturing formworks, molds, scaffolding, or other auxiliary devices for the double-curved parts pose high costs and entail lengthy production times.

The fabrication elements, components, and details of continuous curvilinear surfaces bring into question the immanent geometrical characteristics of complex forms. In spite of the vast amount of research that has been conducted on developable surfaces, meshes with planar faces, and the problem of segmenting a surface into a geometrically optimized net (Xing et al. 2011; Pottmann et al. 2007; Pottmann 2006; Liu et al. 2006; Akleman et al. 2005), sufficient practical and inexpensive solutions for the rationalization of freeform structures with planar faces are not currently being proposed (Brell-Cokcan et al. 2009a). If the construction of buildings with the freeform geometries commonly designed with CAD software is not yet ready to go mainstream or at least continues to remain only barely attainable, we would like to foreground the question of how to construct such complex buildings with the most commonly used fabrication techniques.

2. Unfolding Software

The objective of our investigation was the computation of double-curved structures in order to fabricate them from flat sheets of material, using common fabrication means such as laser cutters or three-axis CNC routers. Our software, called UNFOLDING, assisted in the search for ways of fabricating complex freeform surfaces (figure 1); it is dedicated to the generation of such developable surfaces, especially from anisotropic materials (Akleman et al. 2016). Being directionally dependent, anisotropic properties are not the same in all directions. This means that such materials are bendable along one direction (or a few directions), rather than across them. Consequently, these resources can withstand much greater stress when it is applied across their bendable direction (Saunders et al. 2014).

To represent a complex geometry by segmenting it into quadrilateral panels, UNFOLDING uses an approximation technique that generates developable ruled surfaces of cylindrical pieces with the same tangent planes. The software is capable of decomposing any freeform shapes into quad-patches (figure 2). By utilizing quadrilateral mesh, each panel is bounded by four corners. Since a complex form is unfolded and converges onto flat panels without distortion, the in-surface distances of the panels remains unchanged. Each set of two panels are connected via one overlapping corner with an appropriate fastener, with no geometric torsion. The corners of each pair are elements of the same plane.

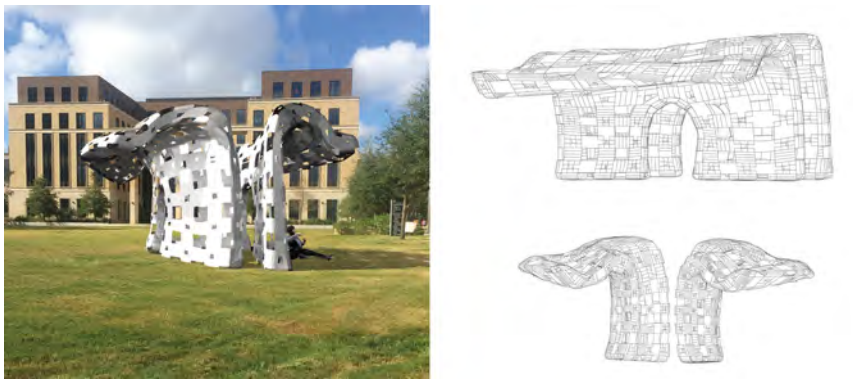


Figure 1. UNFOLDING impacted the general formal characteristics of the students' designs (A pavilion designed by Zachary Newchurch).

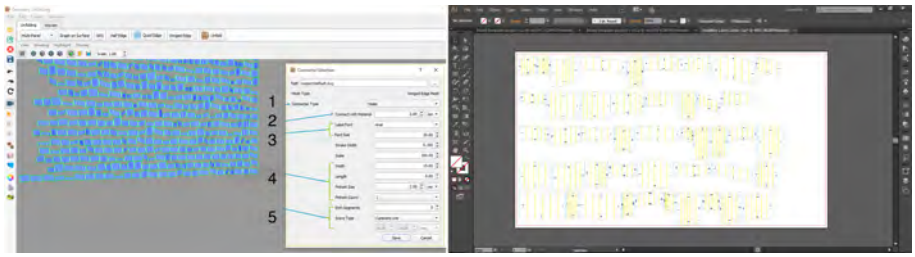


Figure 2. After the unfolding process, UNFOLDING offers a variety of settings to generate an appropriate SVG file for Adobe Illustrator. These settings are available: 1) Connector Types, 2) Material Thickness, 3) Labels Properties, 4) Component Properties, and 5) Line Properties.

UNFOLDING reconstructs the geometry of a complex planar mesh with flat-shaped panels (called quad-edge panels) when the vertices of the planar mesh are unfolded (Akleman et al. 2016). In the original mesh, by computing the corresponding vertices of the adjacent faces, the software displaces a two-dimensional quad-edge piece for a one-dimensional vertex, in order to generate a hollow mesh. Removal of the vertex nodes results in the final model no longer having filled corners. The panels can be bent and pushed inward or outward, transforming the figure into a non-planar shape. Accordingly, the faces of the mesh are replaced with juxtaposed panels that are plane-tangent at their corners. By assigning different construction values to the mutually-linked panel parameters, a range of possible sizes, surface characteristics, and connecting points can be dynamically designed to serve as faces (figure 3). Depending on the sizes of the panels and the underlying quad mesh structure, some open voids may be left in the final model after joining the panels together. These voids can be minimized or maximized. UNFOLDING offers rational trade-offs among panel size, the spatial distribution of any voids, structural rigidity, material consumption, and required cutting time.

By incrementally editing the construction values of the Flap and Bridger (figure 4 & 5), the entire model can be restructured. Then, the current mesh can be

unfolded. What makes UNFOLDING so appealing is the ability to easily control the geometrical relationships of the panels via the graphical user interface, which supports a better understanding of the final design. The quadrilateral panels can be inexpensively cut from flat sheets of material. However, economic considerations (in terms of materials and ease of fabrication) are not the only reason we developed UNFOLDING. Equally important is the empowerment of designers to interactively edit architectural freeform shapes according to different design requirements, a consequence of which is the extension of knowledge regarding geometric representations of complex designs.

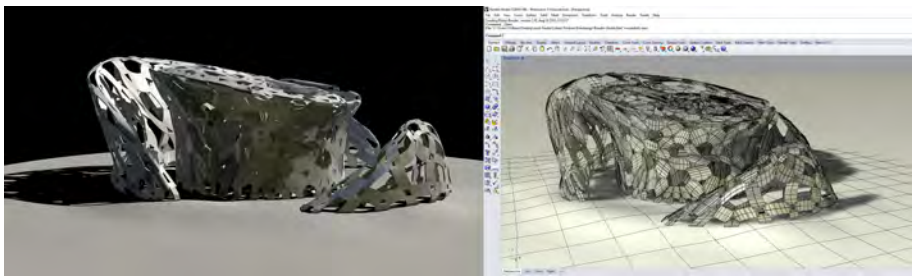


Figure 3. UNFOLDING is used to unfold a complex freeform into planar panels (A pavilion designed by William Palmer).

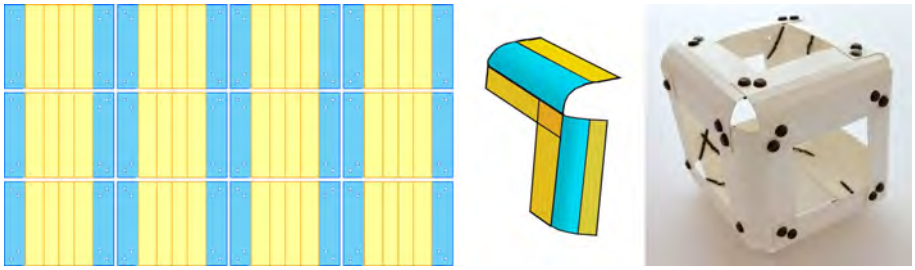


Figure 4. By using UNFOLDING, a three-dimensional form is divided into quadrilateral, single-curved panels.

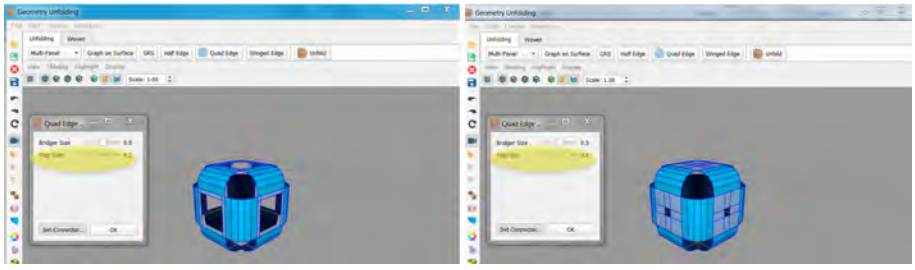


Figure 5. By altering the Flap size, a designer can change the size of voids between the panels.

3. Unfolding In Practice

As an attempt to extend the potential of digital design and fabrication possibilities for future architects, UNFOLDING enables the identification of likely problems with double-curved structures and the incorporation of constructible solutions. Within the context of a design studio held in the College of Architecture at Texas A&M University, first-year architecture students used UNFOLDING to design complex lightweight geometrical pavilions; the goal was to demonstrate the software application through an architectural project. As an open source type of software, UNFOLDING was freely available to all students.

The students began with polygonal mesh approximations of their pavilions in 3D forms that closely resembled the shapes of their original designs. Then, they unfolded the double curves of different freeform pavilion structures into multiple planar panels that were simple 2D-developable polygons (figure 6). The resulting models were much more easily fabricated. By using our software, the students were able to examine how their designs could be discretized in ways similar to the given models. The result was based on approximating a 3D model from single-curved panels. Thus, students learned how to address the design and fabrication process of large-scale architectural forms. Unfolding their hollow meshes allowed them to investigate how a complex form can be divided into quadrilateral, single-curved panels.

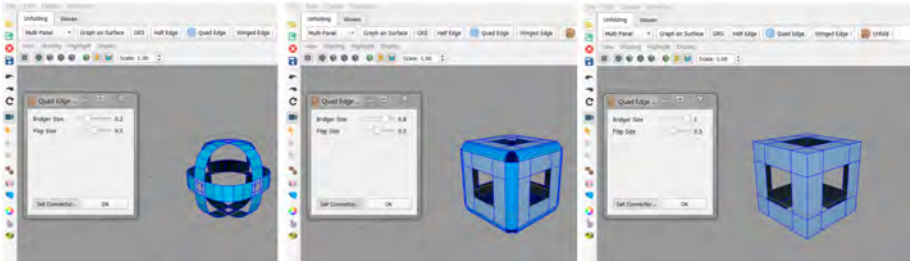


Figure 6. By changing the Bridger size, a designer can adjust the curvature of the panels.

Prior to this experience, our custom software was also used in a separate design studio at Texas A&M University. Another group of first-year architecture students designed and physically constructed a wide variety of complex sculptures with quad-edge panels that closely resembled the shapes of their original designs (figure 7). Through different examples, the concept of quad-edge data structures was described for those students not already familiar with the particular mathematical concepts. For instance, the quad-edge data structures rediscovered by David Reimann were discussed. Based on these structures, a wide variety of symmetric Platonic and Archimedean polyhedrals with uniform length edges could be constructed, simply by replacing each edge of a regular polyhedron with a square-shaped equilateral and equiangular polygon (Reimann 2015). By reviewing Reimann's examples, the students came to see that reconstruction of a spatial structure with only square, quad-edge panels might cause bumps or craters to accommodate the additional length of the panels. In some cases, the students also

observed that the squares had little planar deformation. Consequently, to be able to control the Gaussian curvature of the structure, they determined that they could utilize a series of parallelograms or trapezoids instead of squares. Based on this observation, they came to understand the significance of the multi-panel unfolding system offered by UNFOLDING.

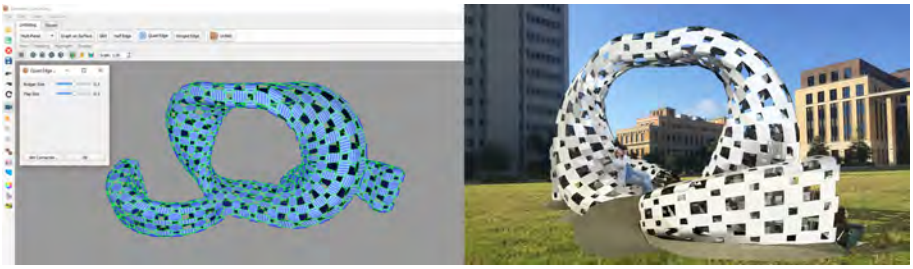


Figure 7. A first-year architecture student generated quad-edges panels to unfold the surfaces of his pavilion structure (A pavilion designed by Sean Williams).

In the studio, students were granted a significant amount of freedom to express their ideas regarding the design of freeform surfaces in response to the project brief. Since the process of translating continuous complex curved designs into built forms and controlling the quality of freeform surfaces can both be troublesome (Araya 2006), especially for freshman with only minimal knowledge of specific materials and the fabrication process, UNFOLDING assisted them with breaking down complex forms into simpler units. The general formal characteristics, surface representations, and geometric expressions of the pavilions were affected by the breaking of their continuous surfaces down into constructible entities (figure 8). Therefore, the inevitable main question arose of how to achieve a stronger correlation between the implementation of UNFOLDING's constraints as a design tool and the architectural considerations of the pavilion project. According to the procedures followed during the fabrication process, students strove to fine-tune their designs and lock in the number of desired control points of their mesh. Changing the number of control points helped students alter the number of cut pieces and the overall assembly process, but changed the final appearance of their pavilions.

Each model exhibited different types of panels that called for a great many laser-cut pieces. Having laser-cut pieces with accurate dimensions and precise placement of all holes gave students tight control over the location and orientation of the panels in their final assembly, which was essential when dealing with complex systems. After creating their panels, they exported the overall outline to Adobe Illustrator as an SVG file. In Illustrator, by using different layers and changing the stroke colors, the students adjusted the layouts of their panel drawings on laser-cut templates.

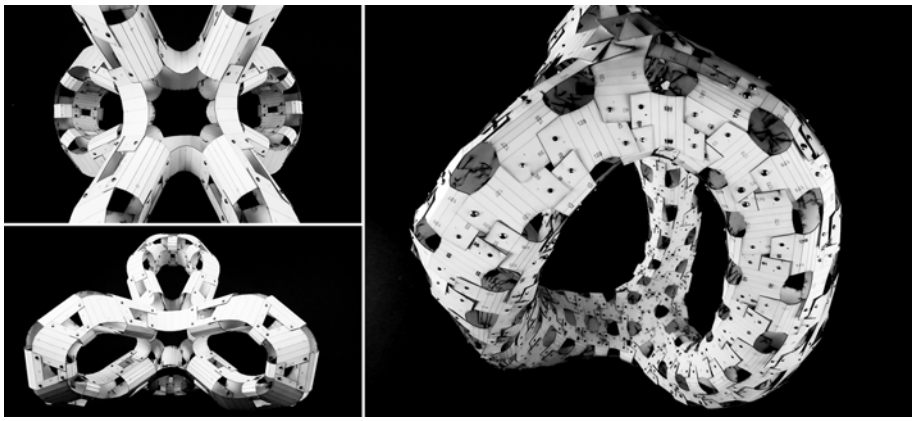


Figure 8. UNFOLDING helped first-year students to design and fabricate several sculptures (The models were made by Nicholas Houser, Jessie Bullard, and Benjamin Hergert).

Consisting of a set of geometric control features, our software helped students drive their designs toward constructible structures. For instance, the software offered the possibility of changing the geometry of any curved panels and the gaps between them. In addition, depending on the Flap size and material rigidity, students had the opportunity to modify the pinhole sizes of the cut pieces to the exact dimensions of their fasteners, alter the total pinhole count, or establish sufficient spaces for holes. After precisely cutting the connection holes of each panel, the panels were connected at their corners with brass split-pin fasteners. Using this type of fastener helped students speed up and simplify the assembly process.

In their projects, UNFOLDING was used as a design development and fabrication tool. By providing a well-defined assembly process, UNFOLDING's quad-edge data structure was particularly suitable for assembling a large number of planar panels. The software simplified the construction process in such a way that construction professionals who may not have extensive experience in this area could assemble the components with only minimal instruction. Thus, students simply assembled the quad-edge panels by matching identical corners, which were given pairs of face and vertex identification numbers (figure 9). In general, the percentage of students who found the fabrication process challenging was quite low. For a few of them, assembly of the panels was relatively time consuming, due to the variable sizes and shapes of the panels. Mainly, though, these students had a difficult time finding the right panels. Incorporating this observation directly into the logic and process of panelizing complex forms will be a subject of our future research. In UNFOLDING, reduction of the average assembly time should be built around sorting the dispersed cut panels into an organized system.

To provide the required bending capacity for the panels, each was laser etched according to straight crease paths. Folding along each scored line and across the entire panel accommodated a small bending radius. In UNFOLDING, depending on the required bend angle, material stiffness, and Flap size, a designer is able to adjust the number of scored lines and etch segments.



Figure 9. By facilitating the assembly process, students assembled the panels by matching their identical corners (The model on the right was made by Jason Casto).

Being under slightly more compression allowed for bi-directional radial folds on the panels. Therefore, inward or outward bending became possible. With respect to dihedral angles between the original mesh faces, the bended panels adapted themselves to retain the corners connected in the same tangent plane. Besides providing bendability for a sheet of material, the scored lines also enhanced the textural quality of the final models. In general, the scoring direction of each panel needed to be oriented with its correlated vertex axis. Since some materials had special bending preferences for exhibiting optimal bendability, the direction of the scored lines, and consequently the direction of the panel placements, also corresponded to the stiffness, orientation, and degree of anisotropy of the material (figure 10). In other words, for each panel, the primary bending direction of the material was parallel to its correlated panel vertex. Therefore, these young designers were bound to the constraints imposed by the material properties to finalize the geometry of the panels.

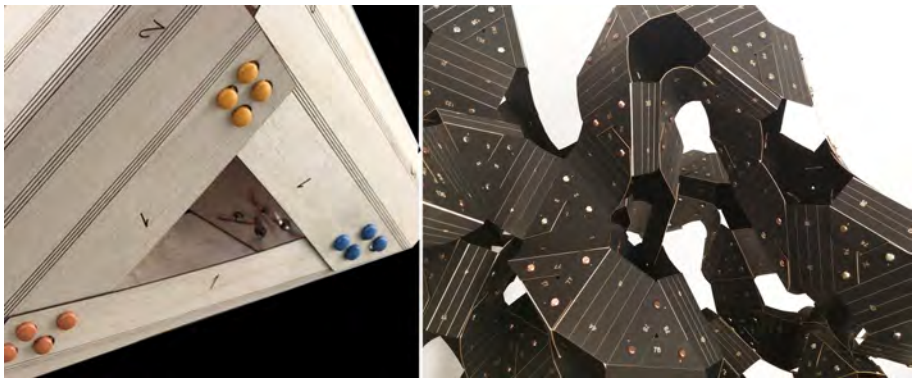


Figure 10. Using anisotropic materials that their properties are directionally dependent can affect the stability of the entire design (The model on the right was made by Arialle Dempsey).

Students were allowed to use a variety of materials to construct their models. They needed to be light but stiff enough to withstand loads and minimize deformation when pressure was applied. At the same time, the material could not be so rigid that it did not allow for the flexibility needed to bend the panels. After much consideration, students decided to use poster board for their scaled prototypes since

it does not have a preferential bending direction. Thus, with no isotropic bending preferences in the material, in the students' prototypes the direction of the scored lines of each panel was dependent only upon the bending direction of the panel in its final placement.

Since the choice of fabrication technique influences construction time and cost, UNFOLDING encouraged students to further investigate the most cost-efficient fabrication methods, while producing precise one-off components of complex structures. In the end, they came to realize that successful projects emerged from collaborations among designers and a wide scope of variables such as mesh structure, desired stability, selected means and methods of fabrication, properties of the material, cost of supplies, and assembly time.

4. Conclusions

UNFOLDING has the potential to provide a basis for designing multi-layered lattice structures. By opening up new dimensions in the design and fabrication of complex freeform structures, this software is an attempt to promote the potential of CAD software by embedding material properties and production methods into the design process. By employing UNFOLDING in the context of two design studios, we attempted to make architecture students better capable of taking advantage of new opportunities, focusing their attention not only on transforming freeform designs into buildable constructions, but also on giving rise to new architectonic possibilities.We observe that the biggest problem turned out to be designing waterproof meshes. When students worked with meshes on Rhino, they could not make waterproof forms. In order to connect pieces, students needed to have topological connections to describe a waterproof virtual model. Unfortunately, most common shape design software such as Rhino, allow creating non-manifold, i.e. non-water-proof, polygonal meshes (Martti 1988). Such models do not have complete neighborhood information. If neighborhood information is missing, it is not really straightforward to turn the virtual shapes into physical structures. This is an interesting software problem since the concept of 2-manifold meshes and waterproof models have been around almost for 30 years. We have developed strategies to repair the shapes using other software such as Autodesk Maya. We hope that introduction of this problem will create a push for software industry to guarantee to obtain waterproof shapes or provide methods to repair the models.

Acknowledgments

Under the supervision of the authors, UNFOLDING was used in two Foundation Design Studios (ENDS 106 and 108) in the spring and fall semesters of 2016 at the Texas A&M's College of Architecture. The authors would like to thank all the students in both studios. The authors want to particularly thank Shenyao Ke and You Wu for developing of UNFOLDING. In addition, the authors want to thank Maryam Mansoori and Jayson Kim for helping students in ENDS 108. This work was partially supported by the National Science Foundation under Grants NSF-CMMI-1548243.

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APPLICATION OF DIGITAL FABRICATION TECHNIQUES TO RECONSTRUCT ANCIENT MACHINERY

A Case-study of Su Song's Water-powered Astronomical Clock Tower

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Abstract. The restoration of ancient machinery involves a number of aspects, including manufacturing procedure, materials, and scales. Portions that cannot be confirmed should be regarded as variable parameters of the reconstructed design, and therefore, there is no single result. The goal of reconstruction is to establish a prototype of ancient machinery with its mechanical engineering techniques and crafts. The problem of this study is how digital fabrication tools used in architectural design can be applied to the reconstruction of ancient machinery with the water-powered armillary and celestial tower as an example. The objective was to synthesize results that comply with historical records in a systematic, modularized, and parameterized manner and consider the feasibility of using modern digital fabrication and materials. With the procedure, we can reduce the difficulty of ancient machinery reconstruction and provide a reference for the reconstruction designs of ancient mechanical technology and crafts, and mass production made of different materials and scales in the future.

Keywords. Digital fabrication; Ancient mechanisms recovery; Innovative design.

1. Introduction

The water-powered armillary and celestial tower is an automated mechanical astronomical demonstration device invented by Northern Song Dynasty polymath Su Song. Construction of the tower began in 1086 and ended in 1093. The original tower was destroyed during the Jingkang Incident in 1127 during Southern

Song Dynasty. Although Su Song's son, Su Xie, had preserved the manuscript of the tower, no one could understand it and thus the tower could not be reproduced (Chen 1996). The astronomical clock tower was a great Chinese achievement in the telling of time and powered machinery, so the loss of the original tower exerted a great impact on the science and technology development in China. At present, the most original data regarding the tower comes from the book Xin Yi Xiang Fa Yao, which was penned by Su Song during the Shaosheng era. This treatise gives a detailed account of the tower's overall functions and its more than 150 components and contains over 60 illustrations.

The water-powered armillary and celestial tower is claimed to be the earliest mechanical clock in the world. This automated mechanical astronomical demonstration device was originally used exclusively by the emperor. Approximately 12 m high and 7 m wide, it was vertically divided into three levels: an armillary sphere at the top for astrometric purposes, a celestial globe in the middle to demonstrate the movement of celestial bodies, and a clock that gives the time automatically at the bottom. The entire tower is powered by water and can tell time accurately. Joseph Needham, a renowned British expert in the history of science and technology, indicated that the tower was the direct ancestor of astronomical clocks in Europe (Needham et al. 1956). The timekeeping device of the tower comprises clock wheels and a five-level pagoda-like structure. Figure 1 displays the relevant records in Xin Yi Xiang Fa Yao. The timekeeping device is similar to the cuckoo clocks that exist today; the wooden figures on the structure strike percussion instruments at fixed times of the day. The clock wheels and the five-level pagoda-like structure announce the time by visuals and sounds. As the clock wheels turn, the five-level pagoda-like structure displays the current time, and the wooden figures on the structure strike percussion instruments.

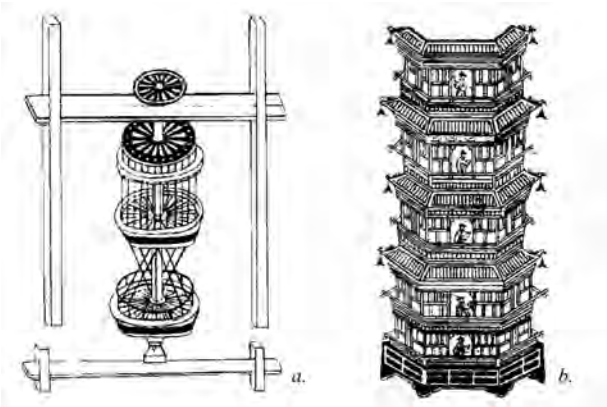


Figure 1. The drawings of a) clock wheels and b) five-level pagoda in the book of Xin Yin Xiang Fa Yao.

In his book Time Wars, Jeremy Rifkin (1987) writes, "Every culture has its own unique set of temporal fingerprints. To know a people is to know the time values they live by." The time system in ancient China was associated with the

use of timers. Back then, the units of time used included year, month, day, shi, and quarter. Shi and quarter are the basic measures of time in a day; the former refers to the hour, and the latter refers to snicks on the indicator-arrows of a clepsydra. Three time systems were used during the Song Dynasty: the Duodecimal Time Law, the Clepsydra Time Law, and the Geng Dien Law of the Decimal Time Law. The clock wheels work for all three time laws at the same time.

1.1. RECONSTRUCTION RESEARCH FOR ANCIENT MACHINERY AND METHOD

The reconstruction of ancient machinery involves the use of ancient mechanical principles, mechanical engineering, and crafting skills (Lin &Yen 2006). Based on historical records, Lin and Yen (2006) divided ancient machinery into three categories: documented and proven, undocumented and proven, and documented and unproven. The historical records that they examined included ancient texts, historical artifacts, archaeological materials, and existing objects. Documentation refers to non-material historical records, whereas proof means existing authentic objects.

Numerous mechanical inventions were made in ancient China. Nevertheless, many creations were not preserved. Those that were documented as being created successfully but not passed down physically are classified as documented but unproven (Yen 2007). The water-powered armillary and celestial tower examined in this study falls in this category. The primary objective of creative mechanisms and machine design is to systematically produce design ideas that meet design specifications, needs, and limitations. Lin and Yen (2006) mentioned that the goal of reconstruction is to establish a prototype of ancient machinery with its mechanical engineering techniques and crafts. Portions that cannot be confirmed should be regarded as variable parameters of the reconstructed design, and therefore, there is no single result; diversity is inevitable. On this basis, they proposed a procedure of reconstruction research for ancient machinery as a method of studying mechanical history.

1.2. RESTORATION HISTORY AND DIGITAL FABRICATION IN ARCHITECTURE FIELD

Based on ancient text, the original concept of reconstruction was proposed in architecture, where relevant academic achievements and engineering technology development are the most comprehensive. In western architecture, the development of the concept of reconstruction and engineering technology began in the nineteenth century, when French architect Viollet-le-Duc proposed the concept of "style-like repairs". Later, in the late nineteenth century, British activist William Morris introduced the idea of "Accomplish Nothing Protection". In recent years, "scientific repair" became mainstream in Italy, which influenced the signing of the Venice Charter in 1964 and UNESCO's Convention Concerning the Protection of the World Cultural and Natural Heritage in 1972. This shows that western attitudes and methods with regard to the restoration of historical sites are converging together. In contrast, the concept of reconstruction in architecture and engineering technology in the east has never been considered systematic. In recent years, the

exteriors of historical architecture have been found to differ significantly before and after reconstruction due to ancient literature being incomplete or lost, which made reconstruction difficult and the results uncertain. It wasn't until recently that the western methods of scientific repair were available for the restoration of ancient architecture, particularly digital tools. An increasing number of digital models are being created as a means of preserving or reconstructing architecture. This is otherwise known as reverse engineering (Mill et al. 2013).

Digital fabrication has already been widely discussed and applied in architecture for decades. Aside from setting a trend for digital architecture style, technological progress has also solved some problems that building construction has faced in the past using the latest computer-aided design (CAD) and manufacturing (CAM) techniques. An example is the Basílica i Temple Expiatori de la Sagrada Família (commonly known as the Sagrada Familia) in Barcelona, Spain, the construction of which began in 1882. However, the design that the primary architect Antoni Gaudí (1852 ~ 1962) produced was too complex to build with the technology back then and remains unfinished to this day. In 2000, scientists and architects began collaborating with the help of CAD/CAM techniques and overcame limitations using digital fabrication. As a result, the temple is slated to be finished in 2026 (Burry 2016). In Asia, there is research on how to preserve existing historical buildings in digital images and digital 3D models, such as using 3D scanning point cloud technology, building information modeling (BIM) technology, parametric modeling, and even multimedia animation and virtual reality components (Baik et al. 2013; Boeykens, Himpe and Martens 2012; Boeykens and Neuckermans 2009; Chen 2008; Chévrier and Perrin 2009; Shah and Mäntylä 1995; Murphy et al. 2013). These achievements in the restoration of historical sites in architecture may be applicable to the reconstruction of ancient machinery and solve common problems.

2. Problem and Objective

The restoration of ancient machinery involves a number of aspects. Current methods entail the use of suitable modern fabrication methods to present the scientific technology and design thinking of ancient machinery and then using such methods to further study the restoration of ancient crafts and equipment (Lin & Yen 2006). The problem of this study is how digital fabrication tools used in architectural design can be applied to the reconstruction of ancient machinery with the water-powered armillary and celestial tower as an example. The objective of this study is to integrate digital fabrication with the reconstruction of ancient machinery and borrow the theoretical and practical foundation of digital fabrication in architecture to propose a procedure of using digital fabrication techniques for ancient machinery reconstruction. With the procedure, we can reduce the difficulty of ancient machinery reconstruction and provide reference for the reconstruction designs of ancient mechanical technology and crafts in the future. Furthermore, the digitization and parameterization of the reconstruction process also enables the replication of the original piece in different sizes, thereby achieving the long-term goal of popularizing science education.

3. Introduction to the Case Study

The case analysis approach was adopted in this study. We used the water-powered armillary and celestial tower displayed at the Museum of Ancient Mechanical Science and Technology in the Southern Taiwan University of Science and Technology. Due to the limited space at the museum, the size of the tower reconstructed there is only a third of that documented in literature; it is approximately 1.5 m high and 0.70 m wide and consists mainly of timber and metal. The clock wheels, as shown in figure 2, are the primary devices that record and present time in the water-powered armillary and celestial tower, displaying the Duodecimal Time Law, the Clepsydra Time Law, and the Geng Dien Law of the Decimal Time Law with concrete visuals and sounds. Containing many cultural connotations with regard to the allocation and use of time in ancient China, the clock wheels are exemplar timekeeping devices of mechanical clocks in ancient China and a sign of the development of timekeeping devices in China reaching maturity.

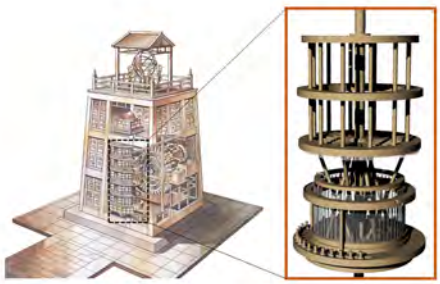


Figure 2. The clock wheels of Su Song's water-powered astronomical tower.

4. Apply CAD / CAM Techniques in Restoration and Construction Process

The process of reconstructing the clock wheels in this study was based on the Procedure of Reconstruction Research for Ancient Machinery developed by Lin & Yen (2006), thereby including three steps. The first step involves collating historical records, analyzing the timekeeping technologies in ancient China, and using the results to understand the mechanisms of the clock wheels and divulge their cultural foundation and design specifications. The second step is to design a mechanical structure based on the illustrations and text in Su Song's Xin Yi Xiang Fa Yao and inducing its design requirements and restrictions, thereby systematically obtaining a reconstruction design in accordance with the mechanical technology and crafts of the time. The third step involves the use of CAD/CAM techniques to construct a physical model of the reconstruction design obtained in the previous step and digital fabrication tools to create a reconstruction model that can be duplicated.

4.1. HISTORIC RECORD STUDY

First, the authors collated the materials of clock wheels based on the ancient book of Xin Yi Xiang Fa Yao for research and collation. In addition, it is important to examine the Duodecimal Time Law, the Clepsydra Time Law, and the Geng Dien Law of the Decimal Time Law in the water-powered armillary and celestial tower. There are eight wheels in the clock wheels. See table 1.

Table 1. The features of clock wheels.

Wheel Item	*Name*	*Pagoda Level*	*Feature*
First	Head wheel (天輪)	-	gear wheel
Second	Gear tooth wheel (擒牙機輪)	-	gear wheel
Third	**Daytime drum-gong wheel (晝時鐘鼓輪)**	**First floor**	**gear teeth**
Fourth	**Early and mid time wheel (晝夜時初正輪)**	**Second floor**	**figures**
Fifth	**Quarter-keeping figure wheel (報刻司辰輪)**	**Third floor**	**figures**
Sixth	**Night-time clepsydra gone wheel (夜漏金鉦輪)**	**Fourth floor**	**gear teeth**
Seventh	**Night-time figure wheel (夜漏司辰輪)**	**Fifth floor**	**figures**
Eighth	Night-time arrow wheel (夜漏箭輪)	Fifth floor	arrows

The first is head wheel connected to the celestial globe. The second is gear tooth wheel driving the whole of wheels to rotate. The third is daytime drum-gong wheel for the top level of the pagoda which are three figures. The one on the right strikes a gong on the even-numbered hours, the one on the left rings a bell on the odd-numbered hours and the one in the middle marks every 15 minutes by striking a drum in his hand. The fourth is early-mid-time wheel for the second level which are 24 figures with a different one appearing in the opening every hour holding a plaque indicating the current hour. The fifth is quarter-keeping figure wheel for the third level which are 96 figures with a different one appearing every 15 minutes, holding a numbered sign that refers to the appropriate 15-minute interval. The sixth is clepsydra gone wheel for the four level. The seventh is figure wheel for the five level. The bottom two levels are for the nighttime. On the fourth level, there is only one figure that strikes a gong located above his head 38 times throughout the night, beginning at dusk and continuing until dawn. On the fifth level, there are 38 figures, with one appearing with each strike of the gong to indicate the appropriate nighttime interval. Thus, this level is empty during the daytime. The last is arrow wheel sustaining the clepsydra gone wheel.

4.2. RECONSTRUCTION DESIGN

The documented but unproven reconstruction design was considered from the aspect of reconstruction synthesis based on the design principles collated in table 1 and solve problems with current engineering design techniques and methods. The objective was to synthesize results that comply with historical records in a system-

atic, modularized, and parameterized manner and consider the feasibility of using modern digital fabrication and materials. For example, historical records indicate that the inner diameter of the first level of the five-level pagoda-like structure was 6 chi and 7 cun, which equals approximately 2 meters today. In the 1/3 scale model, that would become 67 cm, as shown in figure 3. Furthermore, illustrations of the spoked wheel in ancient texts show 16 spokes arranged in a radial and equidistant manner. To obtain the digital copies of ratios between the thickness of the spokes and the wheel, the information of ancient images is translated into 2D CAD drawings.



Figure 3. The scanned images of pagoda's first level in Xin Yin Xiang Fa Yao.

With regard to the wheel design, as shown in figure 4, the inside of this level contains the daytime drum-gong wheel, which controls when the wooden figures on the outside tell the time using gear teeth. The daytime drum-gong wheel turns on the same axis as the clock wheels and spins a full rotation once a day. It has a total of 120 gear teeth. There are 12 gear teeth for the odd-numbered hours of the day and 12 gear teeth for the even-numbered hours; the two sets of gear teeth are evenly spaced along two circles inner part the wheel, one every 30 degrees. The outer part of the wheel has 96 gear teeth, one for each quarter of the day according to the odd- and even-numbered hours of the Clepsydra Time Law.

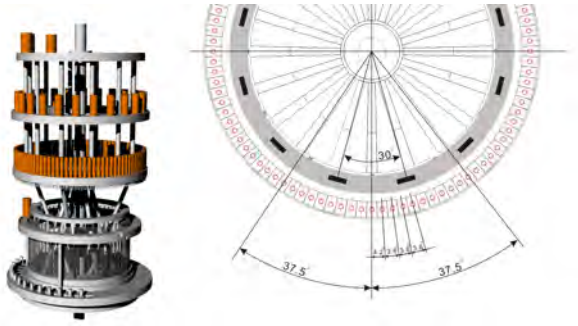


Figure 4. The angle of gear teeth and the location of figures on daytime drum-gong wheel.

The wooden figures on each level of the five-level pagoda-like structure have their own purposes; some tell the time by striking percussion instruments, and some hold plaques to tell the time according to the Duodecimal Time Law, the

Clepsydra Time Law, and the Geng Dien Law of the Decimal Time Law. The details are presented in table 2. In this step, the clock wheels were analyzed based on the illustrations and text in the Xin Yi Xiang Fa Yao, and 3D graphics software was used to create a digital model for reconstruction.

Table 2. The time law of each floor in five-level pagoda.

Pagoda Level	*Door position*	*Figure actions*	*Time law*	*Time of timekeeping*
First	Left, middle, right	The left rings a bell, the middle strike a drum, the right strikes a gong	Duodecimal time law, clepsydra time law	Daytime
Second	middle	24 figures hold plaque	Duodecimal time law	Daytime
Third	middle	96 figures hold plaque	Clepsydra time law	Daytime
Fourth	middle	A figure strikes a gong	Geng dien law	Night time
Fifth	middle	38 figures hold plaque	Geng dien law	Night time

4.3. RECONSTRUCTION MANUFACTURING

Reconstruction manufacturing involves turning the design results of the previous step into a physical model, which is an achievement and display of research on ancient machinery. The design results were imported into a CAD/CAM environment. The manufacturing method for each component was discussed. Components that would be manufactured using CNC and laser cutting were redrawn using 2D CAD, whereas 3D digital fabrication models were drawn for those that would be constructed using rapid prototyping as shown in figure 5a. Dynamic simulations were then conducted to check for errors. The design model was disassembled and categorized based on the manufacturing technique chosen and materials planning. The physical components, which were assembled as shown in figure 5b, are produced through the above mentioned digital manufacturing tools as CNC router, laser cutting, and 3D printing.



Figure 5. a) Redrawing 2D CAD drawings and 3D fabrication model. b) Fabricating all of the components and objects.

5. Conclusions

Using digital fabrication techniques, the process of ancient machinery reconstruction can be divided into three stages, as shown in Figure 6. The first stage is histori-

cal archives which is to clearly present the design requirements based on historical data, and then regularizes the design problem. The last step of historical archives is regularization that means a clear design specification. The second stage is reconstruction design which is to parameterize and modularize the reconstruction design contents after design synthesis and analysis. The step of parameterization is to dismantle and parameterize the ancient machinery to classify different materials and proportions in digital environment. The last step is modularization, which is to standardize the same size and shape of components, and then reduce material consumption and manufacturing costs. Final stage is reconstruction manufacturing, which materializes the design, including finishing the construction drawings, dismantling digital model, and manufacturing physical objects. Therefore, the step of materialization is based on different materials and scales to make the whole model decompose into several components. According to the results of this study, the model can be decomposed into four kinds of components, including ready-made components, 3D printing components, computer-numerical-control components, and laser cutting components.

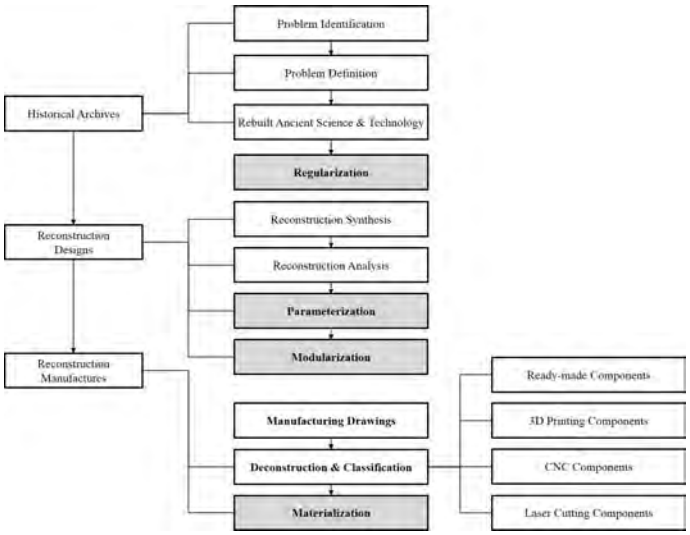


Figure 6. Procedure of using CAD/CAM technology to restore ancient Chinese mechanisms.

This study proposes a procedure of using digital fabrication techniques for ancient machinery reconstruction. The result of this study offer a new approach to easily fabricate ancient copies of different scales and materials owing to computer-aided design and manufacture. It is helpful to promote science education. The manufacturing materials of this study are mainly wood with reference to the ancient mechanical materials. Future studies will continue to examine whether the procedures will be different when the ancient machinery is made of different materials.

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WATERJET AND WIRE-CUTTING WORKFLOWS IN STEREOTOMIC PRACTICE

Material Cutting of Wave Jointed Blocks

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Abstract. In the context of stereotomic practice, advanced fabrication with waterjet and wire-cutting of interlocking wave geometry has opened up new possibilities for crafting stone modules with precision and efficiency. This paper discusses the utilization of machined cutting techniques, the processes and workflows of fabricating joint systems for arched and vaulted surface geometries. It presents a comparative study with multiple criteria; such as geometry, method, material, machine and workflow. Furthermore, this paper presents research into the comparison between abrasive waterjet cutting and wire cutting of modules in stone and foam.

Keywords. Stereotomy; Wire Cutting; WaterJet; Wave Blocks; Workflow.

1. Introduction

The use of cutting methods in stereotomic practice has significantly changed due to advances in computational design and manufacturing workflows. Developments in abrasive wire and waterjet methods have further advanced cutting capabilities for complex curvilinear geometry. This paper extends previous research into the development of fabrication options using ruled surface geometry for interlocking wave joints, "Stereotomy of Wave Jointed Blocks" (Weir et al. 2016). Here, EPS foam prototypes were produced using a robotic hot wire end effector on a 6 axis Kuka Robot arm (figure 1). All the faces of the polygonal shape were split up into non-repeating edge loops. An appropriate interpolation level was set for any curves, and the edges within the edge loop were used to find coordinates and angles for the robot to move through.

The research explored hot wire cutting as a representational process since it is cost effective and efficient for prototyping iterations of the wave blocks at various

scales. Even with this consistent method, there were numerous outcome errors explained in section 4. In comparison, the research continued with a test wave block in stone (figure 2) cut using an 11 axis abrasive wire-saw with 10mm diamond wire at 50mm per second.



Figure 1. Two pass cutting sequence of EPS Foam blocks (Image source: Weir et al. 2016).



Figure 2. Left: T&D 11 Axis abrasive wire-saw cutting (Gosford Quarries). Middle: Base wave block Mt White sandstone Right: Sandstone cut blocks (Image source: Fernando 2016).

Building up from this, the present paper first discusses current precedents for manufacturing and material performance of different joint systems with waterjet and wire cutting machine methods. Then reports on ongoing research into wave joints that were produced with different methods, machine applications and materials.

2. Current Stereotomic Practice

Advanced computation and manufacturing has redefined stereotomic practices' scope and complexity. Burry argues that the once ancient craft of cutting stone by hand to the architect's precise measurement was a 'highly laborious undertaking' (Burry 2016). Fallacara, notes that a renewed interest in stereotomy stems from the fact that 'stone masonry can proceed rapidly with computer-guided cutters that can fashion more complex shapes' (Etlin et al. 2008).

2.1. PRECEDENT WORKFLOWS

Whilst the industrialisation of serial articulated robots for automated tasks was important, now multi-functionality is key, for it 'allows a robot to change from a milling machine to a 3D-scanner, just by switching its end effector'(Braumann & Bell-Cokcan 2012). Enabling better efficiency for multiple tool changes in the

workflow of abrasive wire cutting. For example, a wiresaw end effector can be replaced with the finishing spindle tool without having to re-calibrate the position of the cut object.

Yet the main challenge of using industrial robots is to program their movements efficiently. The developments of plugins such as 'KUKA|PRC'; 'SuperKUKA' and 'HAL' that are integrated into software used for architectural design have provided architects with the potential to plan, simulate and analyse a robot's movement from within a familiar CAD/CAM environment (Braumann & Bell-Cokcan 2012).

A direct workflow between design and robotic tool path for subtractive cutting is demonstrated by recent projects for hotwire applications, such as work by Schwartz (Schwartz and Mondardini 2014), McGee & Pigram (Braumann & Bell-Cokcan 2012), and Søndergaard (McGee et al. 2014). Schwartz and Mondardini (2014) employed the HAL plugin to support the integrated design and prototyping of Abeille's vaults by using the plugin to 'compute the inverse kinematics of the machine, to detect eventual collisions, and solve the orientation of the hot wire in a specified domain of rotation around the wire'. This is significant as robot control data files are generated to work the robot, which allows for a repeated and fast interactive workflow.

2.2. PRECEDENT SUBTRACTIVE METHODS

A number of projects can be traced that explore challenges for stereotomic practice, particularly joint methodologies. For example, McGee et al (2012) and Feringa and Søndergaard (2014), (Carrara Robotics) have demonstrated novel approaches to cutting sandstone and marble with custom developed abrasive diamond saws.



Figure 3. Armadillo Vault, Block Research Group, (ETH Zurich) displayed at the Venice Architecture Biennale 2016 (Image source: Fernando 2016).

Subtractive methods in processing stone range from CNC milling, sawing, wire cutting to abrasive waterjet cutting techniques. Saw blades in the initial roughing stages, produce an efficient cut per unit cost of tooling. Milling machines, usually more expensive, subtract material requiring detailed finishes. Abrasive waterjet cutters use high pressure streams of water mixed with abrasive garnet to erode material producing a thinner kerf. These methods are utilised in projects such as the 'Armadillo Vault' by the Block Research Group, consisting of self-supporting, compression only, mortar-less structural sandstone (figure 3). Employing primarily a saw blade for the cutting sequence of each module for both machine efficiency

and cost implications (Rippmann 2016). The saw blade allows for unique surface textures shown on the inner face of all the panels.

2.3. PRECEDENT IN MATERIALS AND MACHINES

Expanded polystyrene (EPS) foam as a representational technique for complex stereotomic practice is often applied in current robotic stereotomic research. Cutting this inexpensive material with a hotwire, closely links contemporary methods to historical precedent and the 'developed surface of traditional stone masonry' (McGee et al. 2012). Similarly, in the RDM Vault (Ibid 2012), robotic hotwire cutting was explored as an efficient method opposed to dedicated CNC machining; with advantages over traditional CNC milling at an architectural scale including reduced machining time and better surface finish. Whilst limitations include higher production times, rationalization of geometry to ruled surfaces and inaccuracies caused when dealing with the material itself.

Multi-axis waterjet cutting of masonry has been used for Thin Shell Vaulting (Kaczynski et al. 2011). This project uses a 7 axis Kuka KR 100 HA (high accuracy) robot to manipulate a custom built abrasive water jet nozzle for cutting twisted planar surfaces in sandstone. These precedents demonstrate that each fabrication method is heavily influenced by geometry and prototyping material. The resulting outcomes illustrate the existence of a direct relationship between fabrication technique with both the initial shape and the capacity of the machine.

3. Research Review: Wave Jointed Blocks

Planar and ruled surface geometries for interlocking joint surfaces can be efficiently fabricated and assembled, shown in the above precedents. Non-planar or multidirectional joints based on sinusoidal geometries for complex vaulting or dome structures require more research. As a further investigation into new approaches to stereotomic practice, the Robotics Research Group at the University of Sydney explored robotically fabricated joint typologies. Two particular strategies were investigated; a universal multiple-face joint with variable modules in a form and force fitting connection of three intersecting domes (Jung et al. 2016); and a wave jointed block capable of an extended structural ability, concealing the majority of the cutting effort inside the joined blocks (Weir et al. 2016).

Consecutive studies were conducted focusing on workflow when transferred to abrasive wire and waterjet cutting. Sedimentary, metamorphic and igneous stone types are examined in both simplified and complex wave joint geometries. This study utilizes multiple criteria to examine both wire cutting at 1:2 scale (≥12kg of stone) and waterjet cutting at a smaller 1:50 scale (≤400g of stone). The scale is a measure human lifting capacity so that the stone blocks can be efficiently transported. The smallest 1:50 scale blocks measure at approximately 30mm x 30mm x 50mm which is suited for the waterjet machine capabilities.

3.1. GEOMETRY

Further investigation into wave joints, the complex interlocking geometry was simplified to two reverse semi circle arcs (figure 4), due to machine limitations. Block

A is complex in geometry and cannot be cut using the 3 axis waterjet machine, however Block C is the simplified version, a simple parallel extrusion designed for the 3 axis waterjet machine. Block B with a 60° taper resulted in the aggregation of arched structures (figure 5).

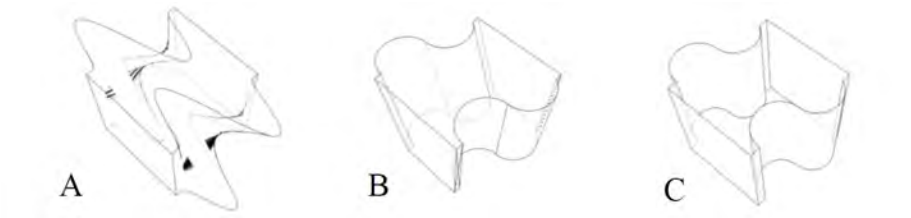


Figure 4. A: Complex wave; B: Simplified wave with 60° taper C: Simplified wave extrusion (Image source: Fernando 2016).

3.2. METHOD AND MACHINE

The waterjet machines used to fabricate the 1:50 scale blocks include the Omax A-Jet multi axis, Marchetti Group Axqua 5 axis and the Maxiem generation 1 1515 with a 30Hp pump (table 1). The smaller test specimens were cut using the Axqua 5 axis due to its availability and proximity to local Carrara marble and granite supplies in Italy (figure 5). The Sydney sandstone specimens were cut using the 3 axis Maxiem and multi-axis Omax A-Jet. 30mm stone sheets were used to cut the modules. The machine settings are summarised (table 1).



Figure 5. 5 Axis Abrasive Waterjet Machine at Material Cutting, Minucciano, Tuscany, Italy.

Table 1. Waterjet machine settings for cutting wave blocks comparison table.

Machine	OMAX A-Jet 6 Axis	Axqua 5 Axis waterjet	Maxiem 3Axis waterjet
Geometry	A	B	C
Pressure	345MPa	400 MPa	345MPa
Abrasive Flow	0.45 kg/min	0.48 kg/min	0.635 kg/min
ParticleDia (Micron)	145microns (80 mesh)	177 microns (80 mesh)	177microns (80 mesh)
Nozzle Diameter	0.40mm	1.20mm	0.42mm
Stand Off Distance	2.0mm	4.00mm	1.8-2.0mm
Speed	96mm/min (approx.)	250mm/min (approx.)	400mm/min (approx.)

3.3. MATERIAL

Simplified geometry block B were cut in a small test series, by using the Axqua 5 axis waterjet machine. These were fabricated from both granite and Carrara marble sheets with a 30mm depth and loosely assembled into arches to test configuration (figure 5).

Table 2. Material / Machine Matrix for Wave Block cutting times, minutes/scale block.

2 a) Waterjet machines	Material Properties			OMAX A-Jet (USA)	Axqua 5 Axis (ITALY)	Maxiem 3 Axis (AUS)
Material Specimen Geometry	Young's Modulus(E) kg/cm^2*10^5	Density g/cm^3	Block Weight g	A	B	C
Sedimentary Rock						
Sydney Sandstone: Mt White	8.9	2.27	400/ 250	2 mins 75mm/min	-	2 mins 321mm/min
Sydney Sandstone: Gosford Buff	8.1	2.23	250	-	-	2mins 321mm/min
Metamorphic Rock						
White Carrara Marble	8.1	2.7	300	-	1 minute 250mm/min	-
Grey Calacatta Marble	7.5	2.6	300	-	1 minute 250mm/min	-
Igneous Rock						
Black Granite (Massa, Italy)	7.0	2.7	320	-	1.5 minutes 200mm/min	-
Aluminium	10	2.7	250	5 mins	-	-
2 b) Wire Cutting machines				6axis Kuka Hot Wire	11axis Abrasive Wiresaw	
EPS Foam (A)	0.00036	0.8-0.9	250	20 mins	-	-
Sydney Sandstone: Mt White (A)	8.9	2.27	15000	-	2 hours 130mm/s	-

As is displayed in table 2, the cutting times, stone types and geometries were further explored, with a particular comparison between the waterjet cutting process at 1:50 scale (table 2a), versus wire cutting machine times comparing sandstone and EPS foam at 1:2 scale (table 2b). Working with the assumption that the cutting time is dependent on a variety of factors including scale of block, material density and method of cutting; this demonstrates how criteria impact on the machine processes and end result (figure 6).



Figure 6. Material comparison of simplified wave block geometry B and C in natural stone.

Abrasive wire-saws are only suitable for cutting larger scale modules, and each of the cuts usually require further finishing, while waterjet cutters do not require further finishing as the accuracy of the cut is finer. Furthermore, CNC milling of sandstone takes slightly longer than abrasive wire cutting, when tested in 1:2 scale wave block (CNC approximately 4 hours with 3 tool changes).

3.4. WORKFLOW

Consistencies and differences between the primary steps involved in the procedure of cutting with wire and waterjet methods are also of importance (figure 7). The diagram shows the processes and relationships of constant feedback loops between a calibration for each geometric model and the respective cutting machine.

What is significant here is that different profiles for wave joints could be sufficiently tested through the benefit of software versatility that allows changes to the base geometry, while at the same time allowing for different fabrication protocols and material selections.

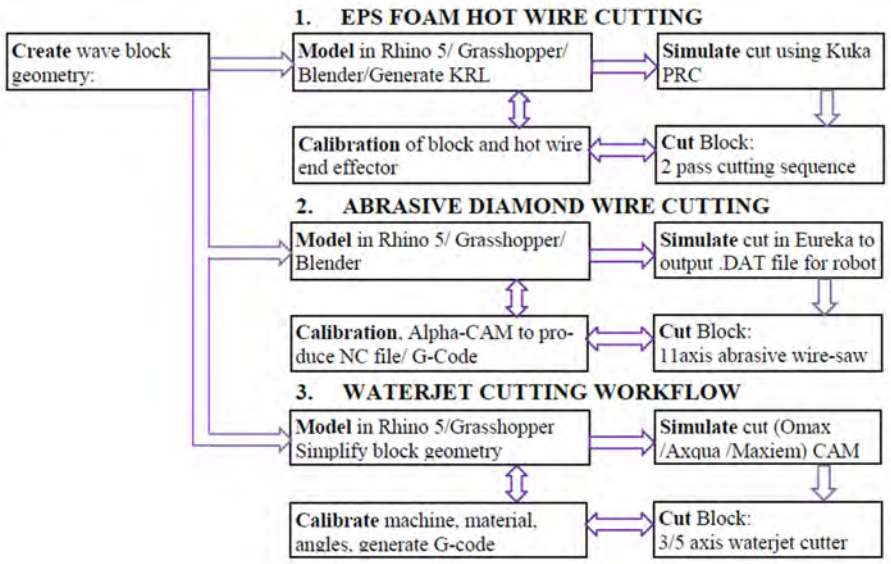


Figure 7. Workflow diagrams showing relationships between methods/machines/programs.

4. Discussion of Results

The transfers between models, machines, file formats, programs and people naturally caused a number of errors which occurred anytime between early design and the final fabrication stages. These are in the following grouped into modelling, machine and material error, and further discussed.

4.1. MODELLING ERRORS

The wave block was initially modelled based on sinusoidal curvature (figure 4), which altered to curvature based on B-Splines. This block was designed with the constraints of the machine to cut sharp angles in stone without breaking (figure 2). The modelling programs used include Rhino 5, Grasshopper, Blender, and plugins including Kuka|PRC. The workflow from Blender to generate the KRL directly to run the robot involved the writing a python script which uses the Blender API to conveniently query the geometry. The simulation of the robot for collision detection in this case made use of Kuka|PRC. Both NURBS (Non-uniform rational B-Splines) and Polygon (mesh) modelling were utilised in the initial design phases of the wave block.

Modelling errors include the initial NURBS geometry modelled in Rhino as simple loft extrusions which was not based on ruled surfaces. Other inaccuracies included using the Rhino transformation tools which are not specifically related to angles and dimensions, but rather are intuitive and based on aesthetic. Parametricising the process of generating the curvature for the cuts in a program such as Grasshopper enabled more controlled outcomes. The most efficient method, was

mesh modelling based on quads which allows the designer to determine the directions of the tool paths. This was particularly effective for both the CNC milling and diamond wire cutting process where the striations became an aesthetic feature and/or assisted in the process of hand or machine finishing the final surfaces.

4.2. MACHINE ERRORS

The machines used to fabricate the 1:2 scale wave blocks include the 6 axis Kuka KR10 with custom hot wire end effector and 11 axis ABB (T&D robotics) Foundry II with abrasive wire-saw. CNC milling had to be utilized in the finishing stages for some of the 1:2 scale blocks due to wiresaw tolerances. Tool wear and tear becomes an issue over time which can alter the final result if not detected early and considered. Laser scanners are used to detect the wear of diamond tools and spindles in the stone industry.

The errors which resulted from these different machines include slightly different workflow, settings and software integration which caused inaccuracies in outcome dimensions. Other specific errors include the machine stalling and fractures of the nozzle or water tubes which causes inaccuracies during cutting.

4.3. MATERIAL ERRORS

Material errors and inconsistencies have to be accounted for when designing in the initial phases of the process. Outcomes alter based on the material density, sheen and grain, and material response to tooling techniques, even when geometries are only marginally modified (figure 8).

At the outset, material characteristics differ in natural appearance, as no two sets of stone blocks are the same. When applying the same geometry (by waterjet cutting sheets of white Carrara marble), outcomes differed visually (even using the same material). Furthermore, materials are affected by tooling techniques, visible in striations evident in both the foam and stone wire cut 1:2 scale modules. Material errors then may include chipping at certain weak points, kinks where there was a machine error or mechanical failure and cracks in the material itself (figure 2, 6, and 8). The optimisation methods should then allow for adequate wire tolerances in the modelling stage of the workflow. In addition, a secondary finishing process is required to make modules fit and interlock. This produces a ‘gap’, which results from the combination of material, method and machine errors. When this is integrated as a ‘shadow gap’, this material error can become a design feature. Material glitches thus can work in favour of outcomes, in an aesthetic sense or as functional aspects. Certain striations or ‘kinks’ in cut stone can actually assist in creating more friction between joint contact surfaces thus delivering better structural stability when joined together, which opens a potential for future research.



Figure 8. Left: Glitch/error/kink in cutting path; Middle: Waterjet cut sandstone striations and erosion due to water pressure; Right: Misalignment of waterjet cut marble modules.

5. Conclusion and Future Research

This paper has discussed the utilization of machined cutting techniques, processes and workflows of fabricating joint systems for arched and vaulted surface geometries. In a comparative study, the multiple criteria of geometry, method, material, machine and workflow for stereotomic fabrication of such wave joints were investigated. The results of these multiple criteria comparisons and case studies illustrate and emphasize inconsistencies, but also opens opportunities. Where a particular challenge arises from the fact that material consists of differing properties that in conjunction with a projected geometry reacts to manufacturing processes. This will need to be further analyzed in relation to how structural performance can be integrated with machine and methodology. Future research in this area will include varying joint geometries informed by both physical and digital structural simulation analysis. It is anticipated that this will consequently impact the cutting method and overall workflow.

Acknowledgements

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TOOLS AS AGENTS IN DESIGN AND MAKING PROCESSES

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Abstract. The inversion of knowledge structure in electronics prototyping platform has allowed designers and architects to design and build reasonably stable mechatronic systems to aid novel material production; these new and hacked computer numeric controlled (CNC) machines are used to explore emerging material constructs and facilitate generative design processes. This paper examines tool making and questions the agentive capacity of such tools in design processes through a case study of a bespoke CNC machine which uses vacuum thermoforming techniques. Through understanding the agentive capacity of CNC tools, the authors suggest that the knowledge structure of tool making is distinctly different from fabrication workflow. This paper proposes an alternative means of understanding the capacity of CNC tools in the design and making process.

Keywords. Digital Fabrication; Tool Making; Electronics Prototyping; Digital Workflow.

1. Introduction

Recent software and hardware advancement have allowed designers to engage design, directly with technology. Open source electronics prototyping platform has allowed designers to tinker with electronics and build reasonably stable and complex mechatronic systems without prior training as engineers. Through open source codes, designers can implement and modify the logic of a device using software coding instead of messing around with the hardware; which traditionally was designed to perform specific application (Banzi 2009). This inversion of workflow flattens the knowledge structure of electronics and essentially democratises physical prototyping of technology (Anderson 2012; Ratti 2015) allowing designers to make bespoke machinery or tools to expand their design repertoire (Ameijde & Carlin 2012; Loh et al. 2016). Like the need to script, the primary aim is to escape the "pre-set" computational or fabrication strategy presented by existing

tools (Fischer 2008; Braumann & Brell 2012; Burry 2011; Davies 2013) in order to gain greater freedom in design; leading to novel techniques, formal expressions and innovative material systems. This emerging hacker culture constructed a feedback loop into architectural design to create a unique platform for design enquiries (Burry 2011; Male-Alemany & Portell 2014; Snooks 2015).

Underlying this phenomenon is increased recognition that the use of parametric software and conventional CNC machineries are slowly defining our design repertoires; the way we design (the workflow and protocol) and its outcome (the aesthetics of the physical artefacts). The tools that we engage in design, can act as agents that have direct impact on our design processes; according to Pye (1974), technology is part of this toolset. Hence, tools have an agentive quality that can be productive in the development of design language, workflow and protocol; this quality can also extend to the material used.

This paper examines tool making and its agentive capacity through a case study; the design and making of a bespoke CNC tool for thermoforming. We asked: what are the agentive capacities of such a tool and how can it facilitate making as knowledge generating activities? In this context, the authors refer to tool as primary equipment that assists in the making process; this includes software and hardware. The case study is a result of a master level design studio at the University of Melbourne.

2. Background

The use of CNC machinery in architectural design and fabrication has created a deep impact on design workflow. In recent years, we have seen a shift in design research from software focused digital design tools (Fischer 2008) towards development of bespoke CNC machines; designed and fabricated by architects and designers, for example FABbots projects (Male-Alemany & Portell 2014), MakeLAB (Ameijde & Carlin 2012) and Insta-llator (Ball-Nogues 2016) to name a few. The Insta-llator is designed specifically to counteract standard fabrication constraints while other examples listed are designed to explore emerging material constructs and as tools which facilitate generative design processes (Male-Alemany & Portell 2014). These tools have a bottom-up approach in expanding the designer's repertoire, not dissimilar to traditional craft practice. The modification and construction of new tools can provide a continuous feedback to the design process and assist in sustaining an evolving and continuing design practice (Loh et al 2016).

As discussed, open source electronics prototyping platform has largely facilitated this insurgence of new or hacked CNC tools. While the implication of this "hacker culture" (Ratti 2015) has been widely discussed as a co-designing tool (Sanders & Stappers 2013) and popularised through global Maker Faires, the effect of electronics prototyping on making processes as a form of enquiry into design is rarely discussed; more specifically, the authors refer to how electronic prototyping as an initial form of tool making can be operative in the making process. Making in this instance, is not just a performative act of reproduction but a creative act of gaining knowledge in design, which involves the construction and transformation of meaning (Sanders & Stappers 2013).

2.1. TOOL AS DESIGN AGENT IN DIGITAL FABRICATION

In order to understand technology as an operative design agent there is a need to position technology, not simply as a tool that is a means to an end, but to carry certain conceptual thought processes which enable design to emerge. Ratto (2011) refers to this form of making as Critical Making, where he situated the hacker culture as scholarly activities that examined making as a social-technological engagement. He suggested that through making, the maker "writes" with material (Nafus & Beckwith 2016) to construct not just the logic of the system but also makes sense of the relationships between user and technology; the process of making sense of these relationships is the critical process of enquiry. Ratto (2011) suggested that the computer should be used as "material" that has a role as a transitional object. The "transition" refers to the exploration of ideas through making where, the design knowledge generated is carried through to the making process. Here, computer as a tool is seen as having an agentive capacity to be able to enhance communication and cognition (Ratto 2001); it has the capacity to carry and deliver knowledge.

The word "agent" and "agentive" should be differentiated to make the argument more precise. An agent is defined as "any element which ... makes other elements dependent upon itself and translates their will into a language of its own" (Callon & Latour 1981:286). According to Malafourisis (2013), an agent is not exclusively a human activity but could be satisfied by material, in so far as the material (tools included) can become an extension of the person. He highlighted the role of material agent through the making of an axe head; using knapping technique on flint. The act of knapping, he argued is an exercise of multiple agents at work; for example, the hand of the maker, the knapping stone and the stone being knapped. Each subsequent strike of the flint determines the angle of the next strike. He suggested that the making of the axe head is not a preconceived image of the axe head within the flint but rather an iterative negotiation of materials.

Agency or agentive capacity is the capacity of the agent to deliver or carry knowledge and therefore has capacity to be useful in design. As Nafus & Beckwith (2016) points out, "knowledge comes not just in the planning, but in the doing." Referencing back to Malafouris's example, the agency of the flint carries the know-how of making and therefore each agent has capacity to deliver specific pieces of knowledge that facilitates the making process. The word agent therefore refers to the "what", while agency refers to the "how" of the activities.

2.2. PROJECT BACKGROUND

This paper focuses on one of four similar research projects that were developed from a 12 weeks Master level design studio. This project was chosen because there is a reasonable degree of complexity and clarity in its fabrication workflow, which is useful for our analysis and exploration of the role of tool as operative agent in design and making process.

The brief for the studio was to design a "machine" that makes architecture at a pavilion scale. The project team consisted of three students working collaboratively throughout the 12 weeks period. The aim of the studio was to introduce tool

making as the starting point of an architectural design project. The objective was twofold. Firstly, while there was a clear programmatic design brief, the approach to the brief was purely from a making perspective; a "wicked problem" where the solution can only be discovered through making (Loh 2015). The boundary of making was defined by the authors through given precedent studies and specific making techniques; in this case vacuum thermoforming. Secondly, we wanted to encourage the students to escape the pre-set condition of existing tools in order to discover novel material aesthetics and design potentials.

Introducing toolmaking in the design studio has its own limitations, primarily due to time constraints and the depth and breadth of knowledge which students need to acquire to complete the design and fabrication of their system. Students have to utilise and work across a range of software and physical tools such as Arduino Microprocessor, Arduino integrated development environment (IDE), electronics prototyping toolkit (including jump leads, breadboards, resistors, relays and servos) and other CNC equipment. At the start of the studio, all participating students had some prior parametric design skill in terms of visual scripting using Grasshopper but had little or no electronic knowledge and making skills. To make the hardware more accessible we introduced the students at an early stage to Grasshopper Firefly 1.0.0.70 and programming language of Arduino IDE; based on C/C++.

3. Case Study: ReConfigurable Edge Mould (REM)

REM (figure 1) was borne out of a desire to explore minimal surface geometry using thermoforming techniques. The ambition was to design and fabricate a mould that is computer numerically controlled to produce variable shaped panels. The material used throughout the project was High Impact Polystyrene sheets (HIPS). The aim of the machine was to make a set of geometrically different panels, each with a defined perimeter dimension of 250 x 250mm that can be accumulated together to form a visual screen to provide privacy in an urban setting.



Figure 1. Reconfigurable Edge Mould as case study, image White, Morse & Bennani.

From a series of initial making experiments and precedent studies, the team highlighted the following issues with the traditional vacuum thermoforming technique in producing variable shape panels using a Formech 508FS.

1. To produce panels with variable geometry, a unique mould had to be made for each shape. The mould was made using laser cut plywood. This technique generated a large amount of material waste.
2. Through making, the team discovered the minimal surface caused by the vacuum former when they introduced a so called "shaping object". The shaping object pushed onto the HIPS and allowed it to drape over the shaping object to produce a minimal surface. The vacuum exaggerated the result and made the surface more legible.
3. The research team had identified the clamping edges of the vacuum forming machine as a key parameter in the operation of the technique.

These observations provided the team with a set of issues and parameters to react to when approaching the design of a numerically adjustable mould that can be used in the Formech.

There had been numerous researches into variable mould design; the background is well documented, in particular the use of multi-pin systems (Schipper 2015; Castaneda et al. 2015). There are three research projects that are relevant to our discussion, although none of these projects utilized CNC in changing the variation in the mould geometry. These projects are VARVAC by HouMinn (Shapiro 2014), AIA pavilion (Riether 2011) and Twisted Concrete (Egashira 2011). The first two projects dealt directly with vacuum forming techniques and examined variable quality of both shaping object and perimeter edge configuration; all the variable edge and shaping object positions were manually adjusted into place from the authors' research. The Twisted Concrete project, although did not use vacuum forming techniques, highlighted the potential of making minimal surfaces with curved edges using fabric formwork.

Learning from these precedent projects, the design team proposed four rule sets in order to produce variation in panel geometry. Firstly, by changing the edge of the panel from a straight line to a quadratic Bezier curve (figure 2A); it generated a depth to the panel which created a minimal surface across the four boundary edges. To create panel depth variation, only three of the four corner points are required to move in the Z direction (figure 2B) with one static point. These corner points can be moved and controlled numerically. The shaping object is used to further deform the surface to create variation; the design team settled on a cylindrical geometry as the shaping object. The flat surface at the top of the cylinder allowed the individual panels to be connected together (figure 2C); here, the aggregation logic is defined through the positioning of the shaping object. To embed the logic further, the panel is divided into quarters where each shaping object defined the centre position of each quadrant (figure 2D). These parameters allowed REM to produce variably shaped panels with the potential to be accumulated systematically in different configurations.

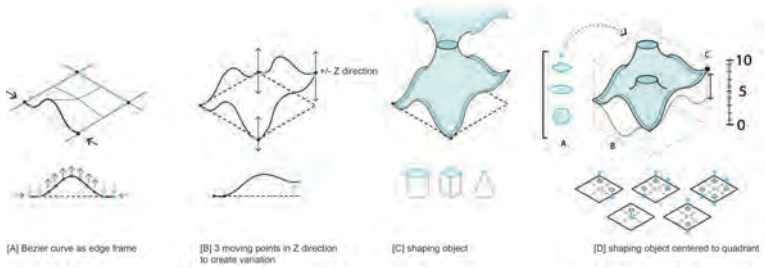


Figure 2. Rule sets of REM.

3.1. PROTOTYPING OF THE MACHINE AND PROTOCOL DEVELOPMENT

The design of the machine expanded on the above rule sets and translated this into material articulation. REM consisted of a two part mould (figure 3). The bottom mould frame [1] consisted of a frame with three moving corners each using a rack & pinion linear actuator [2] driven by servos [3]. In each quadrant of the panel, a shaping object of various heights was inserted or removed [5]. Connecting all four edges were 20mm wide x 3mm thick bamboo plywood strips that are kerfed using a laser cutter to allow the strips to bend and behave like a quasi-Bezier curve [4]. The upper part of the mould [7] functioned as a clamp with duplicating parts so each panel can be clamped and any unformed plastic outside of the formed region can be trimmed off neatly. The input data to the mould is generated through Grasshopper where the Bezier curve edges are simulated using Kangaroo Physics; the edge curves are "relaxed" and allowed to settle into shape with the same edge length. The Z coordinates of each panel is streamed to the Arduino to control the servos.

4. Tool Making as Design Agent

As Fischer (2008) pointed out, engineering tool design typically consists of four phases: "defining the problem, formulating solutions, developing models and prototypes and presenting and implementing the design". The process is iterative in so far as new knowledge is encountered and emerged from the design and making process thereby developing clarity and actively shaping the design of the system.

In this project, the "definition" of the design problem comes from a series of observations and practice of existing making techniques with the aim to develop a fabrication procedure with less material waste. The formulation of the solution came from the isolation of key parameters in the making process and how these parameters (set out in 3.1) were used to generate different aggregation logic of the panels. The design of the machine was tested and prototyped numerous times before reasonably successful panels were fabricated. The struggle of the prototyping process confronted the team with physical problems and made immediate the potential of the system for design (Sanders & Stappers 2013). An example is the kerfed bamboo edge strip which underwent numerous iterations and testing with various materials; including metal, adjustable pins and rubber. The team struggled to find readymade materials that behave in a similar way to the simulated curve

in the digital model; the strip had to be flexible enough to curve and rigid enough to resist the HIPS plastic when clamped together. The resolution came when the team kerfed a 3mm ply bamboo strip to achieve the balance between flexibility and strength. Even then, at acute angles, the edge strip was likely to break in tension.

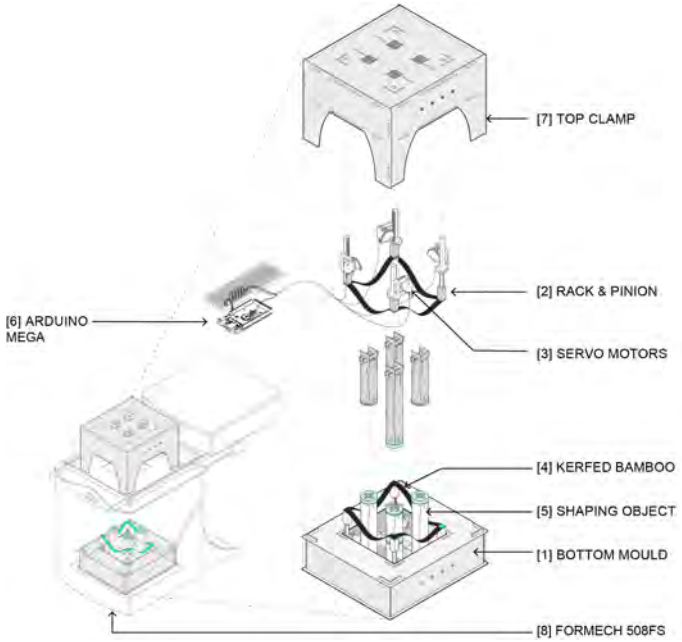


Figure 3. Design of REM showing parts of system.

4.1. AGENCY OF THE MACHINE

Figure 4 demonstrates the protocol of the fabrication workflow. It identifies multiple agents (software, hardware, material and tools) in the making procedure; [A] Grasshopper definition that stimulated and defined the edge curves, [B] the Arduino and electronics prototyping, [C] the linear actuator, [D] the HIPS and the heat from the vacuum former. The physical material (i.e, the HIPS and the kerf bamboo strip) provided resistance to the whole system which relied on the electronics (with the digital data) and the controlled heat to counteract this resistance. The workflow described here is linear which is necessary to make the system legible for its users.

While the workflow diagram demonstrated the flow of information and the various agents at work, the authors suggest that the tool making procedure is perhaps more revealing in terms of understanding the agentive capacity of the bespoke tool (Figure 5).

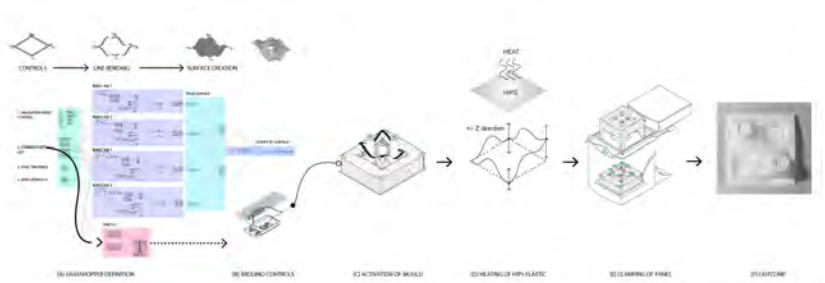


Figure 4. Linear workflow of machine use.

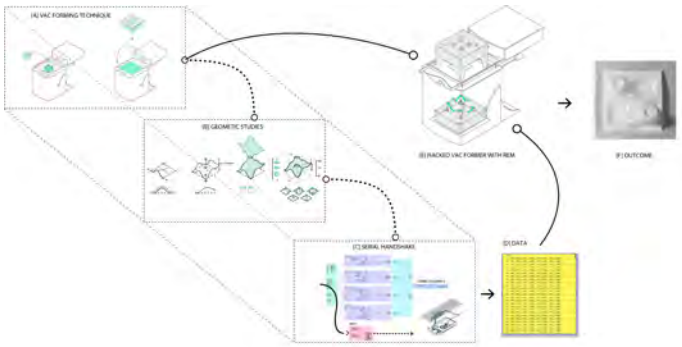


Figure 5. Networked knowledge structure of tool design.

The authors observe that the relationship between tools, materials and techniques are compounded together in this procedure; it is networked compared to linear fabrication workflow. The authors identify three key agentive capacities:

1. The machine aligns the computational data with material performance, in this case geometric data output in conjunction with the kerfed bamboo strip and vacuum forming procedure of HIPS plastic. Here, electronics prototyping functions as a serial handshake (a term from computer science) between the digital data and physical output. Without this alignment, information and performance of the system would have failed to achieve its objective.
2. The tool (REM) has the capacity to collapse, what the authors call the computation history of the making technique; we refer to the knowledge of how to use various tools to perform certain techniques. Electronics prototyping facilitates this collapse by drawing on the data simulated in the script and the know-how of the making process. This is translated into linear motion through the servo which in turn drives the gearing system of the rack & pinion.
3. REM as a novel machine is essentially a hack into an existing toolset (the vacuum former). While REM set out to escape the pre-set condition of the Formech machine, it still worked within its boundary. This allowed REM to become part of the larger toolset in the approach to vacuum thermoforming techniques and is therefore accessible to other researchers and practitioners.

These three layers of knowledge, [A] computational history, [B] geometric studies and [C] digital stimulation and data, (figure 5) allow researchers to understand the construction of knowledge and reveal the agentive capacity of the tools in question. It demonstrates that in this case study, there is no specific agent but the agency of the material and information is fluid (Malafouris 2013).

4.2. DESIGN APPLICATION

The design team speculated on the application of the aggregate panel system to form screens in urban environments as a user interactive play device. The team also tested the use of the variable shape panels as formwork for concrete casting (figure 6). Panel to panel connections were developed as a simple 3d printed push click solution which could be embedded into the concrete cast. These design opportunities were made possible through the design and fabrication process of the custom tool. Here, the tools had a direct and immediate impact on the design language and aesthetics of the system, as set out through the ruleset in the fabrication process.

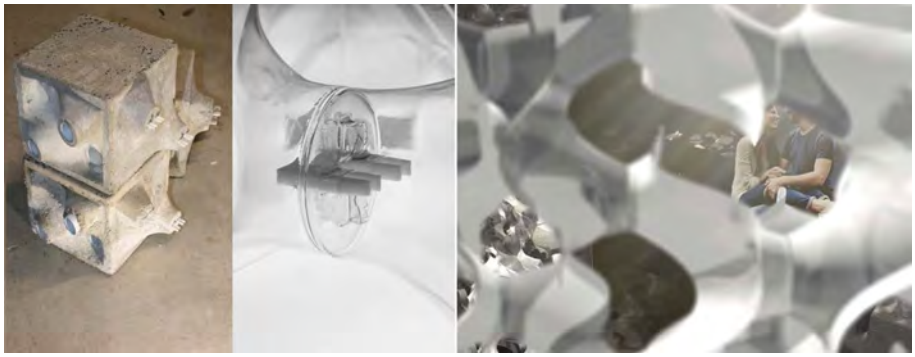


Figure 6. Left, Panels used for concrete casting. Center, HIPS panel connector. Right, Privacy screen in urban environment, image White, Morse & Bennani.

5. Conclusion

This paper outlined the role of electronics prototyping in tool making through a case study and examined its agentive capacity for design. The case study presented is but one instance of many bespoke CNC tools using electronics prototyping toolkit. It brings forth a novel fabrication technique to facilitate generative design processes. The contribution of this paper lies in the presentation of two different methods of understanding the role of tools in design procedure; firstly, through usage as fabrication workflow and secondly, through tool making procedure where the knowledge structure is revealed. Here, the agentive capacities of the system and its relationship to the design processes are clarified. The authors suggest that this can be a useful analytical method for other researchers to understand the role of tool making and its effect on making as a knowledge generating activity. The authors acknowledge that the above analysis has yet to address the

broader scope of how such agency operates across the design cycle as probes and prototypes; this discussion is outside the scope of this paper and will be subject of future research.

Acknowledgement : The authors acknowledge the work of the design team: Frances Mary White, Alex Morse and Maryam Rtel Bennani as well as the technical contribution of Joshua Russo-Batterham. We thank our critics: Jane Burry, Donald Bates, Daniel Prohasky, AnnMarie Brennan, Daniela Mitterberger, Tiziano Derme, Laura Martires and Anna Nervegna. We thank ARUP for their generous technical advice.

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3D Printing

P. Janssen, P. Loh, A. Raonic, M. A. Schnabel (eds.), *Protocols, Flows and Glitches, Proceedings of the 22nd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2017*, 811-821. © 2017, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

SOFT SYSTEMS

Rethinking Indeterminacy in Architecture as Opportunity Driven Research

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Abstract. The research projects in this paper examine the notion of soft systems relative to machine induced material consequences. It asks, how might we integrate processes and methods which leave tolerances for indeterminacy and flexibility into design and construction? The two projects outlined investigate change of state materials paired with automation strategies, focusing on additive processes with thermally induced material configurations and programmable matter with magnetically controlled formations.

Keywords. Robotics; 3d printing; digital fabrication; automation; indeterminacy.

1. Introduction

Sanford Kwinter defines a soft system as one which is "flexible, adaptable, and evolving, [..] complex and maintained by a dense network of active information or feedback loops [and which] is able to sustain a certain quotient of sensitive, quasi-random flow" (1993, pp. 211). In other words, a system is soft when it is driven by dynamics, responsive to change, and comfortable with indeterminacy. In the 1960's soft systems were under investigation in many disciplines, including philosophy and the sciences, and represented a common thread of speculation. In architecture at this time, projects such as the Fun Palace by Cedric Price and Ville Spatiale by Yona Friedman, were investigating the conceptual approaches to soft systems as design opportunities (Bhatia 2012). While Price was more interested in intelligent reconfigurable spaces which would allow for a multiplicity of use, Friedman saw indeterminacy as an opportunity for individual choice and expression.

Before these soft infrastructural proposals in architecture, John Ruskin suggested alternative ideas of soft systems in architecture through his term savageness. Piotrek Swiatkowski in his assessment of this Ruskinian notion, explains the

builders of Gothic cathedrals, often worked in the harsh climates which made construction particularly difficult; he writes, "They frequently made mistakes. Sometimes the craftsmen corrected them, but more frequently they just let them be. Such mistakes, in fact, did not have a negative impact on the beauty of the constructions. To Ruskin, these mistakes are even a central aspect of the beauty of the cathedrals. According to Ruskin the buildings are more beautiful because such savage details are markers of who the workers are, where they live, and what they do." (2014, pp. 43). Ruskin's characterization of savageness suggests soft systems resultant from flexible stonework methods which allowed for imprecision, chance, and response to change. This stochastic craft based method along with the 1960's projects, question the long accepted Vitruvian notion of firmitas and suggest potential for embracing indeterminacy in architectural design and construction.

In computation today, soft systems are integrated through computational approaches which leave tolerances for imprecision and uncertainty (Köppen 2016). In soft computing, the word soft draws on the meaning related to adaptability. However, soft in other contexts can also pertain to a material quality, meaning malleable or reconfigurable, or relate to a geometric property meaning curved or rounded. The subsequent collection of research projects engage in softness, by exploring soft not only as a computational idea, but also as a material and tooling approach for appropriating technology in design. The evaluation criteria and essential questions for the research include the following: How might indeterminate processes be integrated into architectural design and construction and what design opportunities might arise from no longer being constrained by existing methods? What opportunities might arise from developing an automated system which does not rely on direct translation, but instead operates and predicts outcomes within a range of potential results? How might designers work with automated processes which mediate between material volition and the rigid order of computational control?

2. Indeterminacy and Fabrication

Consideration of material properties is essential to the discussion of manufacturing processes (Schodek 2005). In order to achieve desired effects and design intentions, new digital manufacturing techniques are emphasizing the role of material investigation (Kolarevic 2008). Thus, this research examines indeterminacy relative to materials and machines processes which leave room for chance or imprecision. Within the current discourse of soft systems relative to material properties and tooling production, the research is precedented by Roxy Paine's automated sculpture makers (1996-2001) and Anish Kapoors 3d printed concrete (2009). The two material based research projects outlined draw on ideas of indeterminacy in change of state materials by looking at thermally induced 3d printing and magnetically controlled formations. By using unconventional materials, the research seeks to discover ways of developing instrumental rules around material properties and behaviors. It asks, what are the ways design research can promote a greater understanding of materiality relative to fabrication processes not only to allow us to better employ traditional materials, but also to embrace the possibilities present

by new materials? How can we rediscover materiality through experimentation and computation?

2.1. ADDITIVE PROCESSES WITH CHANGE IN STATE MATERIALS

The *Hydronic Printer* is a material and tooling research project which uses a temperature induced change in state material paired with a hydronic cooling additive system. The water based casting system relates to the *Fluid Cast* research conducted at the Design Research Lab at the Architectural Association School of Architecture (2011) and *WX*, a wax sculpture machine, produced by masters students under the instruction of Andrew Witt at Harvard Graduate School of Design (2013). This work differs by exploring the automation of the liquid flow rate relative to the casting process. The method for the research involves a series of melted wax material tests extruded into a container while the water level rises within it. The initial material studies inform the tooling parameters for both water rate and position of wax deposition. These studies also inform a base knowledge of the physics and chemistry of wax formation through hydro induced cooling.

The setup involves heated liquid wax controlled with an extruder and a container with variable water level controlled with a water pump and Arduino (figure 1). The constants include: wax temperature upon exiting the extruder, water temperature, and the rate of wax extrusion. The variables include: water flow rate and extruder position and path. An optimum speed in the pump relative to the extrusion rate results in a cylindrical 3d wax print. When deviating from the pump optimum speed, the width of 3d printed wax changes. The results show that as the water pump speed increases the width of the print becomes more narrow and as the speed decreases the width of print widens (figure 2). The variable water pump speed tests inform a documented taxonomy which shows how the overall geometry of the print changes based on the change in water fill rate (figure 3).

The experiments try to mediate and find an equilibrium between the indeterminate qualities of material behavior and automated precision of machine control. The material tests result in a range of figures from stable to fragile and some to points of rupture. A catalog of the material responses relative to deposition and water flow rate translate into a soft computable process where certain target results are predictable and are calibrated to inform tooling development. The outcome is a 3d printer which uses an automated wax extruder controlled with a robotic arm deposited in a water tank with automated water levels controlled with Arduino and a pump (figures 4 and 5). The research team worked to develop an interface using grasshopper plug-ins Kuka PRC for robotic control and Fire-Fly for Arduino. The interface takes in a desired geometry as input and outputs corresponding water fill rates and machine code for the robotic arm which controls the tool path for the wax extrusion. The resulting printer acts as a demonstration of indeterminate material systems paired with automation in order to provide a critique to the current methods of using support materials in additive manufacturing and draw attention to the potential for materials that respond to change in temperature and moisture.

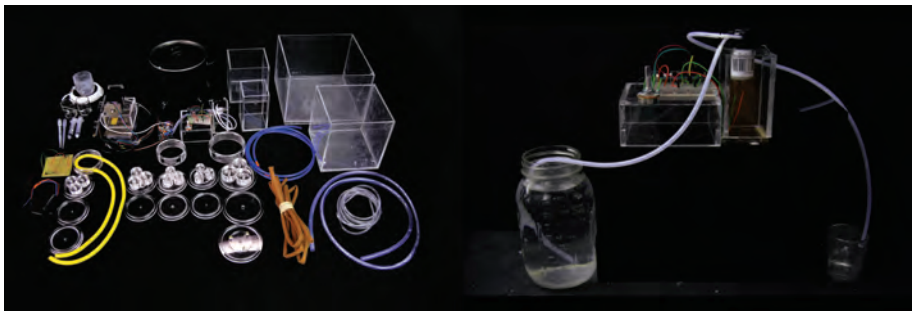


Figure 1. Photographs of research tools and setup including an Arduino controlled water pump.

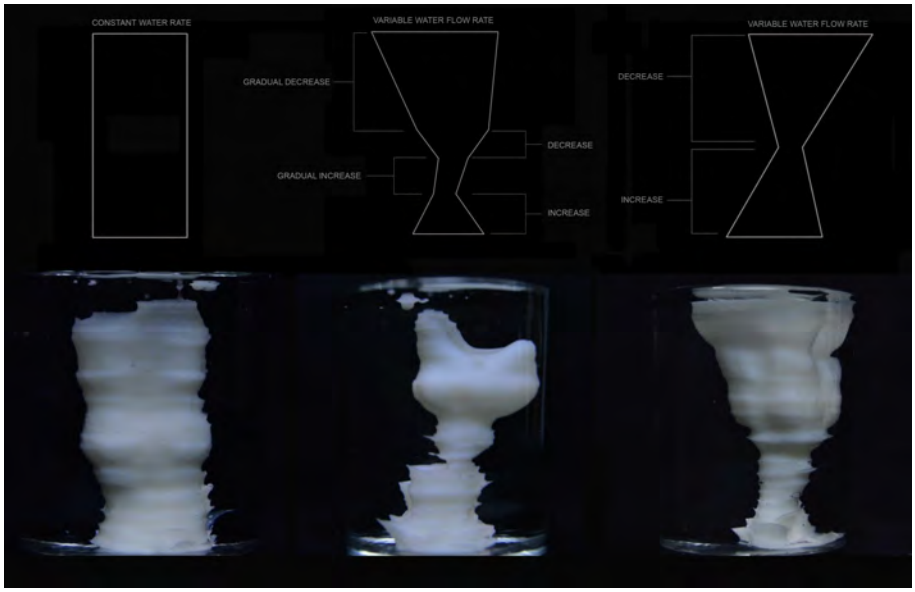


Figure 2. Diagrams and photographs illustrating the change in wax 3d print width based on the change in water fill rate.

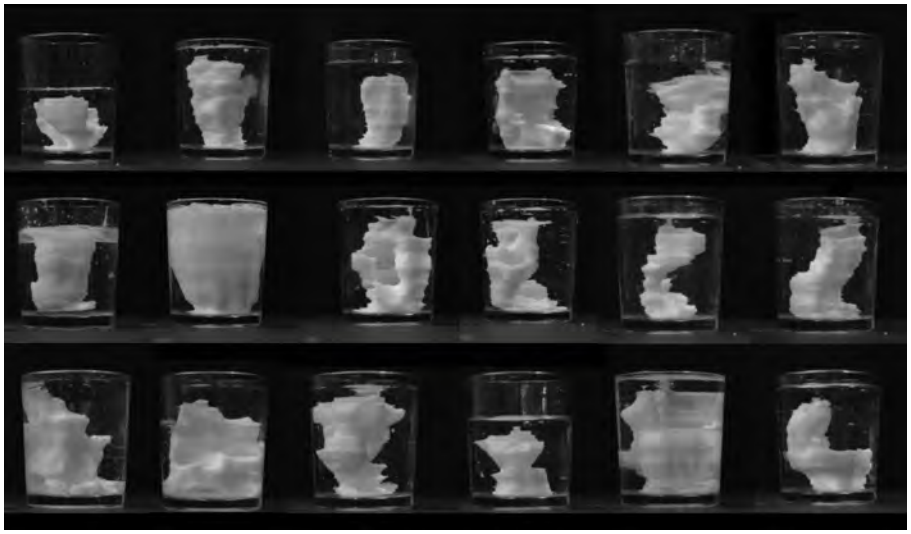


Figure 3. Taxonomy of wax 3d prints showing variations based on water fill rate.

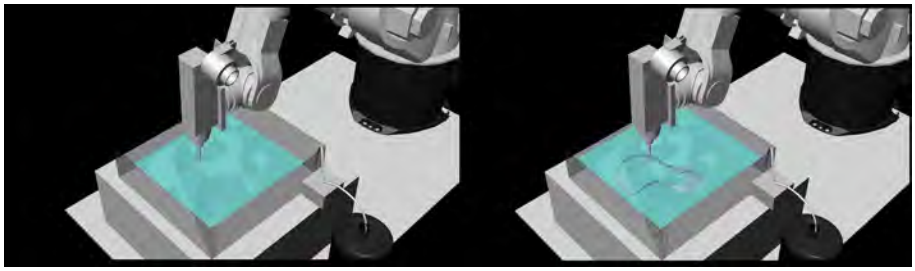


Figure 4. Robotic arm extruding wax into water tank with variable water fill rate.

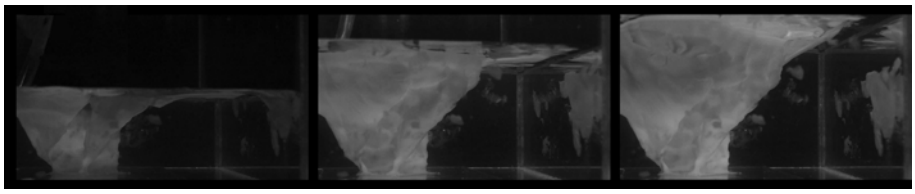


Figure 5. Resulting wax 3d prints shown at three moments in time as water fills the tank.

2.2. PROGRAMMABLE MATTER

Magnetic Formations is a design research project which investigates ideas programmable matter through a fiber reinforced change of state material. It asks, how might a material which is fluid and malleable take on a controlled pattern or form? How might material properties be integrated into the development of tools for fabrication and assembly? Related research includes the projects *Magnetic Architecture* produced by masters students at the Institute for Advanced Architecture of Cataluña (2012), *Matter of Flux* project from Andrew Witt's Expanded Mechanisms course the GSD (2012), and the work of Self-Assembly Lab at MIT (2014). However, the *Magnetic Formations* project differs by testing the range of possiblities capable within a specific magnetic solution with smooth consistency and ideal fluidity for magnetic pull. The research began with tests of variable amounts ingredients for a magnetic solution to produce a balanced ratio of water, polyvinyl acetate, iron filings, and borax. The polyvinyl acetate is synthetic polymer which reacts with the borax to form a precipitate; the final solution provides an ideal viscosity in order for the solution to move with a magnetic force pulling the iron filings within it. The magnetic solution relies upon the locations, strengths, and movements of nearby magnets to trigger changes in form. The magnetic fields produced from these points initiate the iron filing's suspended movement within the viscous solution while the remaining ingredients act as a binding medium. Initial experiments demonstrate how the magnets must be place with alternating north and south poles. Figure 6 and 7 illustrate plan and section diagrams of the magnetic solution and the magnet location and polar orientation.

The research method consists of developing a series of challenges to document and record the various configurations of the material and its limits. The challenges were to produce controlled forms including rectilinear geometries, controlled patterns, columns, and walls (figure 8, 9, and 10). In order to test these constraints, instrumentation is constructed around the solution to act as a scaffolding for holding magnets and controlling their toolpath with 5-axis of movement. Once the solution is magnetically moved and formed into its intended formal composition it is held in place until the water evaporates and it fully cures. Integration of electromagnets into the scaffolding also allow for the activation of the magnetic force for formation of the solution and then deactivated to allow for ease of removal once the curing process is complete. The scaffolding can then be removed to isolate the cured magnetic formation. This project also fits within the domain of soft systems as it operates with in a range of tolerances related to the limitations in magnetic pull and material consistency. While the path and location of the magnets are precisely defined, the reaction of the solution is not exactly known due to changes in the distribution of magnetic fillings constantly in flux. While a range of results become predictable through testing, each repeated experiment differs slightly due to these differences in the filling's location throughout the solution. With the *Magnetic Formation* project the research team accepted these tolerances and subtle uncertainties. By cataloging the distinctions of repeated experiments, the research produces a programmable matter which is predictable with a range of results instead of a specific execution.



Figure 6. Plan diagrams of magnetic solution during formation indicating magnetic pole orientation and location.

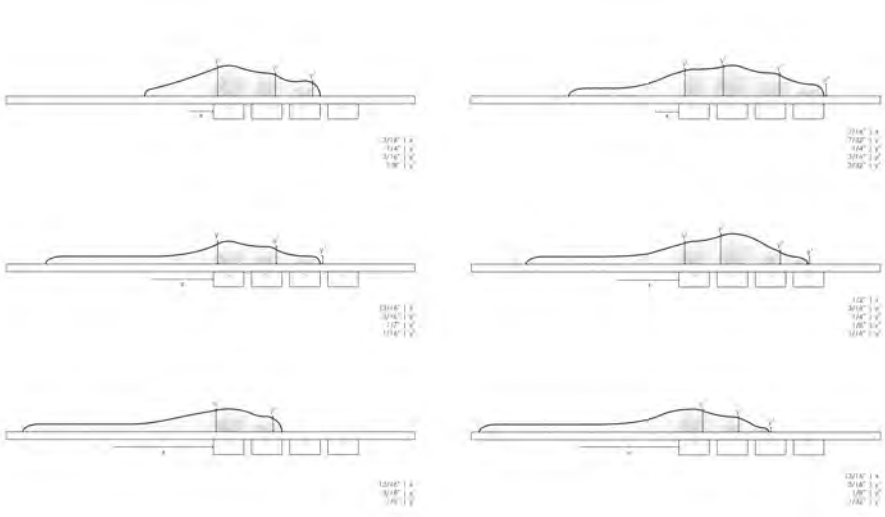


Figure 7. Section diagrams magnetic solution during formation indicating magnetic pole orientation and location.

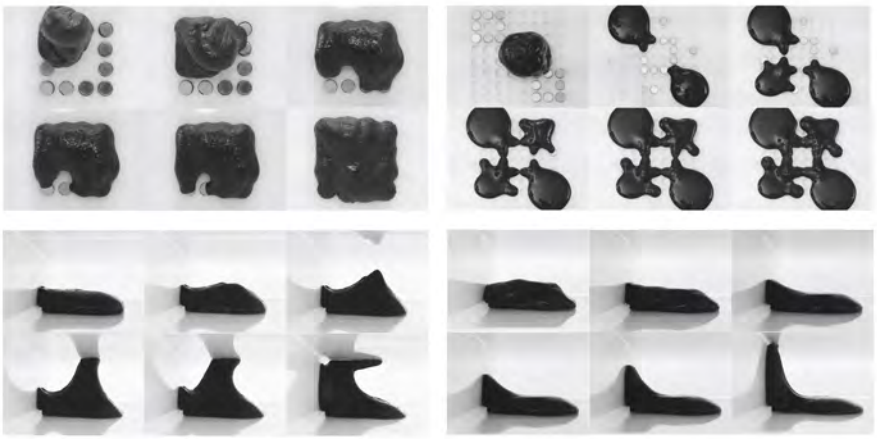


Figure 8. Time based mappings of magnetic solution forming into a square and controlled patterns.



Figure 9. Time based mappings of magnetic solution forming vertically and diagonally as columns and walls.

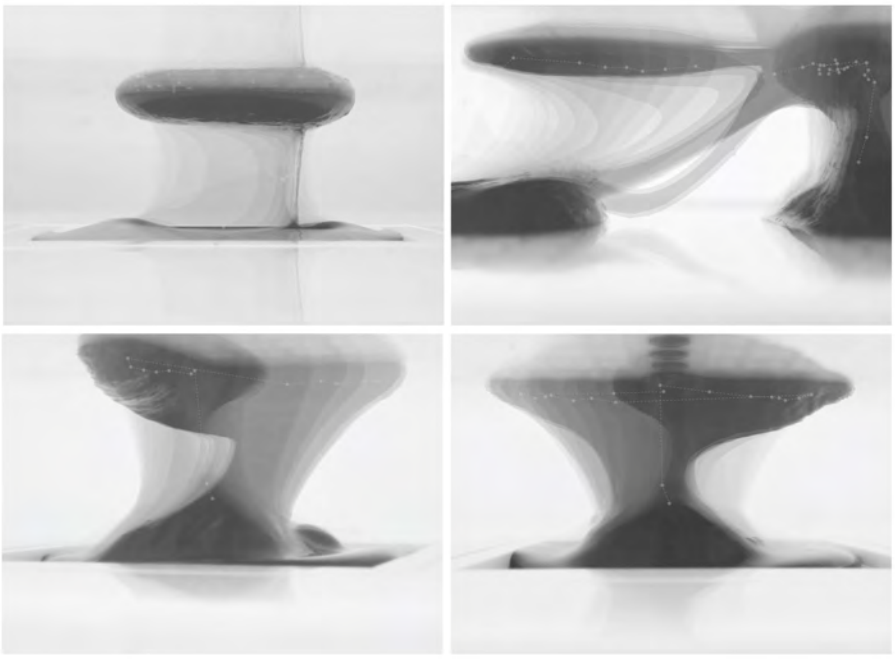


Figure 10. Time based mapping of magnetic solution formation process.

3. Conclusion

This collection of research projects seeks to uncover the capacity of architecture to engage in stochastic processes and strives to bring ideas of material volition into to the discourse of design. While they are initial explorations of soft systems relative to materials and machines; this area of pure research seeks to inform and encourage larger scale applied research which could be adapted to architectural design and construction. This research asks, how we might imagine a design and construction scenario which is no longer confined to prescriptive material dimensions, but is instead driven digitally controlled stochastic material processes? Integrating soft systems into advanced manufacturing and architecture means perceiving the element of chance not as a hindrance, but as an opportunity. However, within this polemic lies the potential to not only rethink indeterminacy in relation to materials, machines, and geometry, but also to ask how design guided by the computation might allow for the study of indeterminacy in regards to human behavior as Price and Friedman suggested. It is within this immense range of potential applications that soft systems provide a way for framing and pursing optimistic alternatives for appropriating technology in design and developing opportunities for rethinking indeterminacy in architecture.

Acknowledgements

This research was conducted as part of a studio entitled, *Material Animation*, at Ball State University in the Spring of 2016. Credit is due to the students, Rachael Henry for the *Hydronic Printer*, and Ian Beals for *Magnetic Formations*. Their willingness to walk into the unknown paired with the creative use of imagination, the power of observation, and an unwaivering dedication to their work made this research possible.

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SMALL 3D PRINTERS / LARGE SCALE ARTIFACTS

Computation for Automated Spatial Lattice Design-to-Fabrication with Low Cost Linear Elements and 3D Printed Nodes

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Abstract. The presented process enables users to design, fabricate and assemble spatial lattices comprised of linear stock materials such as round section timber, aluminum or acrylic dowels and complex 3D printed joints. The motivation for the development of this application is informed by the incredible availability of low cost 3D printers which enable anyone to produce small scale artifacts; deploying rapid prototyping to achieve larger scale artifacts than the machine's effective work envelope is a challenge for additive manufacturing; and the trend in the design computing world away highly technical specialized software towards general public applications.

Keywords. Design Computation; Digital Fabrication; 3D Printing; Spatial Lattices; Design to Production.

1. Introduction

The evolution of digital fabrication technologies such as laser cutting and computer numerical control machining and rapid prototyping bridged the hiatus between digital media and physical artifacts. Design education, research and practice were transformed but more interestingly this trend started permeating into the general public whereby the end-user may become the designer and fabricator. Startups such as SketchFab, OnShape, as well as industry leader backed systems such as 123D and TinkerCad by Autodesk offer 3D content creation software which start from basic levels of complexity seen suitable for broader audiences and progressively scale to functionality found in professional tools.

We inquire for creative applications of rapid prototyping supporting the Maker's trend beyond replication of downloaded or 3D scanned content. How could we break through the limitations of the small envelope, low resolution of low

cost 3D printers to create larger scale perhaps spatial artifacts. How could computation provide tools connecting design and fabrication considerations directly and intuitively. We present a parametric application that enables the design and fabrication of relatively large scale 3D printed artifacts using linear stock elements such as wood dowels coupled with complex 3D printed joints.

Producing large artifacts from small footprint or low-cost digital fabrication machines, such as laser cutters and 3D printers have been investigated in the past (Sass 2004; Dritsas & Kashyap 2005; Sass et al. 2015). Our contributions are in the integration of geometric modeling, analysis and optimization procedures in a nearly instant connection of upstream design and downstream production considerations aiming to be accessible to non-technical audiences.

2. System Overview

The notion of embedding design and fabrication intelligence is expressed by transferring late design considerations such as detail design, production efficiency, material uptake and scheduling upstream. The organization of those is tiered into: (a) Lattice Topology: resolution of the overarching considerations as well as preliminary sizing of elements, (b) Node Topology: resolution of the boundary representation of the solid geometry per node, (c) Joint Geometry: modeling of various types of joint interfaces between the 3D printed nodes and linear elements, and (d) Scheduling and Reporting: where geometric operations are performed to prepare for the 3D printing process as well as the production of metric analysis and assembly assistance reports.

2.1. LATTICE TOPOLOGY

The geometric input to the application is comprised of a collection of lines, dimensions such as the internal and external diameters of cylindrical linear elements and joint detail attributes. Using exclusively round cross-sectional profiles is a constraint for simplifying modeling and analysis but also fabrication and assembly. Complex line networks may be produced by regular drawing, procedurally from mesh or solid geometries or algorithmically by scripting.

Reconstructing the topology of a 3D lattice from geometry includes the conversion of lines into node and edge data structures. It is an incremental process where incoming end-points are compered against all existing nodes to ensure uniqueness. This is a nearest-neighbor search for which we used KD-tree (Bentley 1975) spatial partitioning for accelerating computation.

Every edge is attributed with a diameter and split into two half-edges associated with each of the terminal nodes. Subsequently we focus on nodes to determine the minimum length of extrusion along each half-edge such that no penetration occurs between adjacent branches. The computation is presented in the diagram below (figure 1).

Having determined the nominal size of half-edges, we compute the net length of full-edges as the distance between nodes less the sum of the two half-edges. This results into a complex cutting schedule as dimensions are numerically arbitrary (figure 2). We thus perform rationalization by rounding elements into incre-

ments such as every few millimeters. Clustering-based rationalization strategies (Jain et al. 1999) or one-dimensional cutting stock optimization are performed to further simply fabrication and assembly (Dyckhoff 1990). The residuals from re-dimensioning are distributed into half-edges for symmetry.

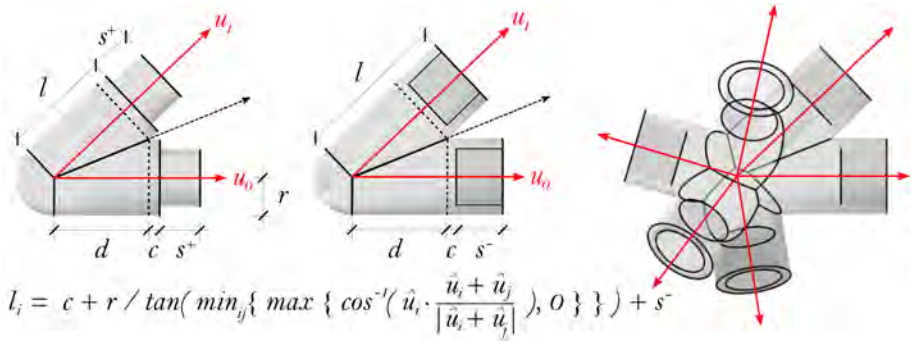


Figure 1. The dimension of each half-edge (l) is determined pair-wise by the minimum angle among all other half-edges by projection on the bisector.

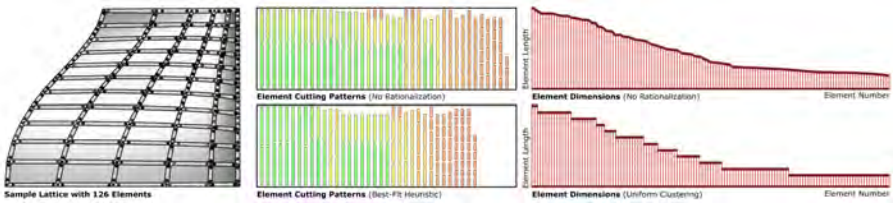


Figure 2. Edge dimension rationalization using uniform clustering simplifies number of types for assembly and cutting stock optimized material waste.

We establish the transformations from world-space to the 3D-printer's build plane. Surprisingly this is a non-trivial task (Xu et al. 1997; Alexander et al. 1998; Byun & Lee 2006) as there are multiple parameters to consider: (a) Stability: printed parts are more accurate if placed upright than resting on a point or edge; (b) Support: it is desirable to minimize the volume of support material to reduce build time and improve quality; (c) Height: reducing the height also reduces build time. Those requirements are formulated as an optimization problem solved iteratively using heuristics.

Use of the average normal from node's edges as the build-plane was sub-optimal in stability (figure 3). We prioritized stability such that basis vectors were selected as the two longest half-edges. This produced acceptable results but there were cases of cruciform nodes where one or more half-edges lied underneath the build-plane. We thus reformulated the search for the pair of half-edges that brings the largest number of remaining half-edges on one side of the build-plane. When multiple solutions are available we minimize the height of the transformed node. In cases where there are no solutions we let a node stand normal on its end or pad vertically the best of previous searched solutions. It is not conclusive which strategy is generally the optimal.

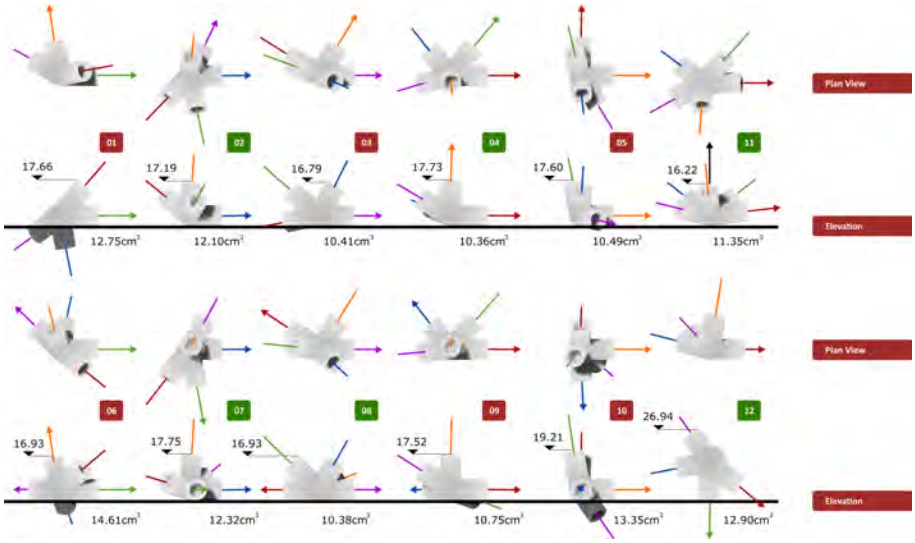


Figure 3. For a 5-edge node there are 1-10 basis vectors combination options. Option 11 uses the node normal, option 12 uses the stand-on-edge strategy.

When the material of the linear members does not exhibit sufficient elasticity joints cannot be assembled axially along the edge directions. We thus support translational joints that can be assembled by motion perpendicular to the edge (figure 4). We select a normal vector per edge, a procedure which is also non-trivial and does not always have a solution for nodes of high valence. Our heuristic for this problem is to determine a normal vector per node by averaging incoming edge directions and use the average of adjacent node normals. This works well for boundary edges of the lattice but interior nodes may suffer from assembly interferences. Solving this problem requires a global search incorporating upstream half-edge length adjustment which is an arguably complex optimization program to be explored in the future.

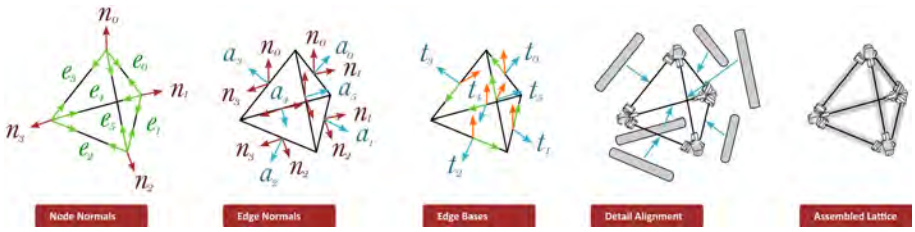


Figure 4. Edge orientation procedure for translational joint types.

2.2. NODE TOPOLOGY

New 3D printers do not require one body per STL file and tolerate overlapped meshes. The initial implementation using multi-body STLs suffered from robust-

ness as it was impossible to avoid non-manifold geometries from coincident mesh edges and vertices. We developed a micro BREP kernel to ensure robustness in resolving intersections of multiple cylinder surfaces.

The key aspect of the BREP system is taking advantage the analytical nature of the geometry namely the network of elliptic arcs as the intersection of equal cylinders. The process is more efficient and numerically stable compared to generalized BREP solvers due to the use of analytical primitives. Pairwise half-edges determine bisecting planes where the elliptic intersections of cylinders are situated. Unless being colinear two edges produce a semi-elliptic arc towards the bisector's direction, otherwise the result is a circle. The common points among arcs and circles are computed and arc segments are discarded by inclusion testing. If the network is completely closed, then the procedure is complete. Otherwise we complete the network with inclusion of circular arcs which belong to the spherical patch at the miter cap.

Scalloping is the process of developing the interface of intersecting cylindrical or tubular profiles used for plasma cutting and welding. We perform this operation for piecing arcs into closed loops that define the trimmed boundary of each linear member. Patches are then unfolded for further processing which is easier in 2D (figure 5).



Figure 5. Segmentation, development and assembly of cylindrical patches.

The elliptic network is polygonised up to tolerance and the generated points are propagated laterally on the trim boundaries of meeting cylindrical patches. This ensures the triangulation produced does not require stitching, an artifact common when approximate trimmed surface boundaries are used.

In the simplest case the application assumes hollow or solid round profile edges interfacing axially with protruding or inset sockets at the nodes (figure 6). This simplifies fabrication requiring only cutting elements to length. The simplest joint detail is the protruding style suitable for hollow linear sections that only require a cylindrical lag appended as terminal geometry. It also produces better results as the node and edge surfaces are flush. The joint may be secured by interference fitting or adhesives. The inset socket type is more complicated as its depth needs to be incorporated upstream in the minimal half-edge length computation. Geometrically it is identical only the cylinder lag is inverted. Inset joints are less efficient in 3D printing material uptake and time of production for the same diameter of linear stock.

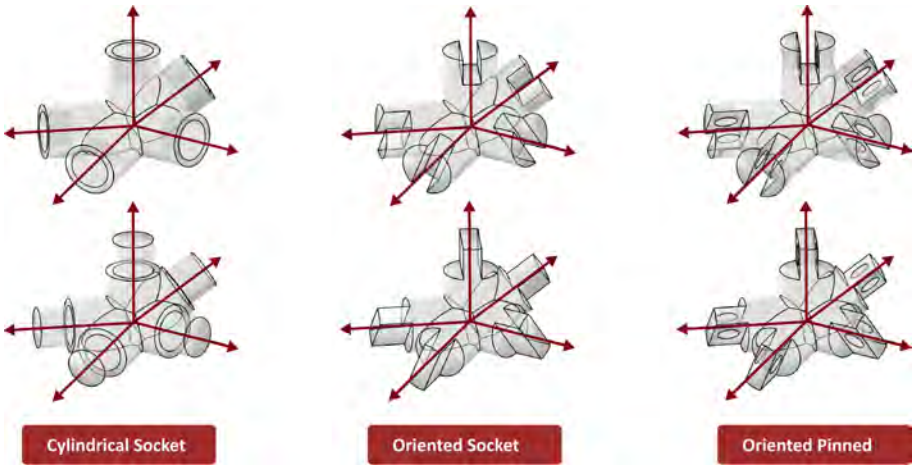


Figure 6. Joint detail options with progressively more complex fabrication of linear members. Left: Axial assembly of solid or hollow sections. Middle: Translational assembly requiring additional cutting. Right: Translational assembly with addition of pinned hinge hole requiring additional drilling.

It is not always possible to assemble lattices axially due to inherent rigidity of triangulated frames. Only the family of affine lattices are possible to assemble axially due to the translational degree of freedom. A translational detail common in architecture and engineering applications where large beams and trusses are assembled is introduced. The linear elements may be slide, glued or pinned into place but this implies additional work in fabrication as slots and holes need to be cut into linear elements. Pin joint connections introduce the opportunity for kinematic lattices as a rotational degree of freedom is relaxed.

The triangulation for the joint has been determined by the topology of the elliptic network. Before the final mesh is assembled there are few operations applied to embed additional details and assist assembly.

All lattice nodes are uniquely identified and annotated to simplify assembly. Two options where explored for annotation: snap-off tags and engraved identifiers (figure 7). The former was guided by the desire to remove printed annotations from nodes in assembly and leave clean parts. The additional complications in optimal orientation of nodes, low resolution of low cost printers and excess printing time using snap-off tags informed the engraved annotation option. To keep the process of mesh generation rapid, clip-off tags are merely injected into each socket whereas engraved annotations are geometrically constructed in the unfold of the cylindrical space and projected back into 3D space.

Constrained triangulation of spherical polygons is non-trivial (Ranka 1997; O'Rourke 2008). Our approach injects a concentric grid of points in 3D to ensure smooth triangulation with minimum number of vertices up to faceting tolerance. Subsequently the boundary polygon and interior points are transformed in plane, triangulated using a constrained Delaunay triangulation and mapped in 3D. For projection we evaluated the transverse Mercator and stereographic projections but

developed a custom scheme that creates better boundary triangles without need for additional edge flipping (figure 8).

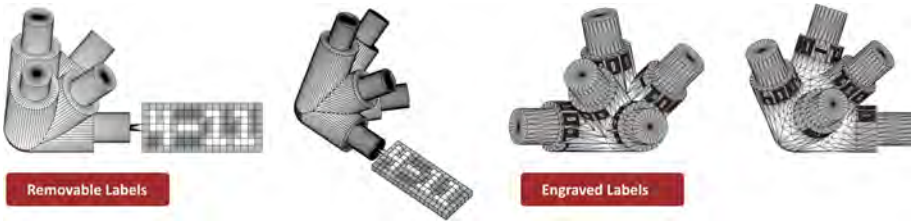


Figure 7. Annotation Embedding Options. Left: Initial solution with removable tags to avoid permanently marking the printed parts. Right: Engraved annotation containing the node and incident edge number.

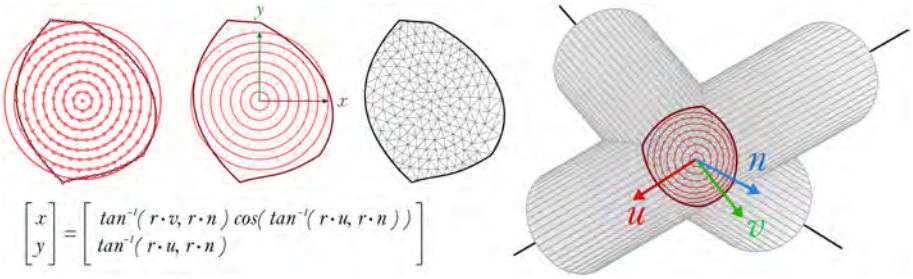


Figure 8. Spherical Patch Meshing: (a) Concentric injection of points in sphere, (b) Projection of cylinder-sphere edges and injected points onto plane, where (r) is the vector from the center of the node to the point on the sphere, (c) Constrained Delaunay triangulation, (d) Projection of mesh onto sphere.

Mesh smoothing may be used to soften transitions among edges. To ensure that annotations and critical boundary edges are retained we first flag the spherical patch and upper circular profile as constrained. Smoothing is performed in two steps: first a polygon subdivision increases the mesh resolution followed by a relaxation step. We investigated Particle-Spring, Laplacian and Catmull-Clark relaxation for which the later produced better results in apparent continuity and smoothness in acute edge angles (figure 9).

The final steps of the process simplify the production of physical artifacts. Meshes are verified as watertight and corrected if required. Nodes and edges are transformed from world to plane coordinates. Layout for nodes employs a rectangular packing scheme in single layer bins. While it is possible to stack layers vertically this is not preferable for most 3D printers, especially filament extruders due to excessive support material use. Additional scheduling data are emitted such as the per node and total volume of 3D printing material, the total net length of linear elements, tabular data regarding identification of nodes and edges (figure 10).

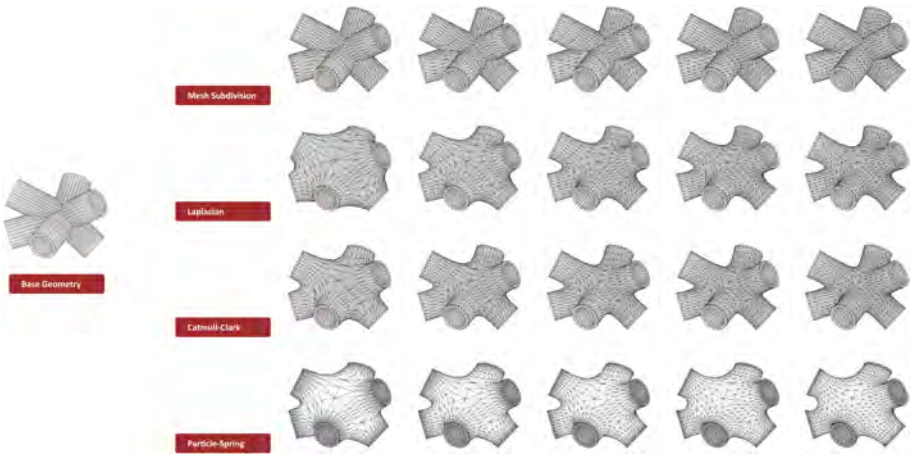


Figure 9. Mesh Smoothing: Catmull-Clark iteration performs best in minimizing 3D printing material at low subdivisions and avoids weakening wall thicknesses at high subdivisions. .



Figure 10. Fabrication scheduling information for 3D printed and manually cut parts.

2.3. CASE STUDY

The application was deployed as part of an assignment in a digital design and fabrication course for second term architecture students with the objective to design and assemble a large-scale lightweight on-campus installation. The materials provided were a spool of PLA filament and fifty 1 meter by 12 millimeter diameter, wood dowels. 64 undergraduate students formed 16 teams and within 6-week, designed and produced preliminary product-design scale prototypes using hollow acrylic rods and large scale installations by the end of the academic term (figure 11).



Figure 11. Sample of student work. Top: Small scale acrylic prototyping exercise. Bottom: Large scale wood dowel installation.

3. Conclusions

We presented a process that enables design and production of large scale spatial artifacts using low cost rapid prototyping 3D printers. The software within its well-defined limited scope, efficiently compacts a large number of operations, integrating modeling, analysis and optimization techniques into small footprint parametric applications directly connecting upstream and downstream design and fabrication considerations. Using 3D printer joinery is perhaps the most effective strategy for additive manufacturing to large scale production. Compared to 3D printing planar elements such as walls and slabs or linear elements such as extrusions which are already typically prefabricated, joints of high geometric complexity are not easy to design and fabricate today. Applying the geometry-oblivious process of 3D printing at complex interfaces makes the most sense and perhaps it may be the first building scale application that makes 3D printing cost effective for architecture, engineering and construction applications.

The current trend in design computation empowering the end-user with limited or no prior design or technical training to imagine and create physical artifacts using simplified design and fabrication technologies is provocative. Basic design knowledge and activities can be abstracted and integrated by computation using

modeling, analysis, automation and optimization strategies. For instance, the ability to span mentally the process of design to production understanding dimensions and proportions, material use, time and effort implications can be hinted. From the end-user's perspective questions such as how big will it be, how long will it take, how much will it cost can be answered. It is also not difficult to embed analysis components to answer simple questions such as will it stand up; or using imaging techniques to answer questions as for how would it look in context. The interesting challenge arising from this trend is relation the knowledge and experience of trained designers and engineers obtained through education and practice is how may end-user efforts foster characteristics such as sensibility, interpretation and judgement. What is contextually appropriate, culturally relevant, setting up experiment assumptions and interpreting the results are non-trivial tasks to fully automate. Nevertheless, supporting creativity and desire to design and make artifacts may contribute inductively towards those goals and the deeper appreciation of design.

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DEVELOPING COMPOSITE WOOD FOR 3D-PRINTING

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Abstract. We present the initial findings of our research project aiming at development of a 3D-printing process for wood composites. The 3D-printing method employed is based on material extrusion principle and utilizes industrial robotics for position and motion control. The unique characteristic of our approach is in the development of the material where we employ exclusively organic components for both the matrix and reinforcement; a decision informed by prioritizing environmental considerations.

Keywords. Digital Fabrication; Additive Manufacturing; 3D Printing; Wood Composites; Robotics.

1. Introduction

The current focus on 3D-printing in design research centres about its two major challenges: scale and material composition. Our project investigates the potential for a novel type of additive manufacturing process based on renewable materials. The majority of available engineering materials for 3D-printing are based on petroleum products such as thermoset, thermoplastic polymers and composites. Technologies are commercially available for printing ceramic materials as well as metal alloys including steel, aluminum and titanium (Materialise 2016). In recent years there have been research developments in investigating materials such as concrete (Khoshnevis 2004), sand (Gramazio & Kohler 2011), clay (Sun et al. 2014), wax (Gardinger & Janssen 2014) for the architecture, engineering and construction industry. 3D-printing is also being extensively researched for biomaterials suitable for medical applications (Gillemot et al. 2010). Our investigation is inspired by developments in organic biocompatible materials.

We explore the spatial deposition of a particulate composite material comprised of wood fibre and an organic matrix originating from animal by-products. Both components are of organic source, renewable and biodegradable. Methods for 3D printing wood composites exist, using pre-impregnated thermoplastic poly-

mer matrices such as Polylactic Acid (PLA) in particulate or filament form using either extrusion or sintering methods (3DSystems 2011; Krassenstein 2015). Compositionally those materials are not very different from engineered timber laminates, wood plastics in general, for example plywood, cross laminated timber and particulate composites such as fibreboards. Those generally suffer in recyclability because the separation of the constituent components is extremely difficult (Frank & Roffael 1998; Pizzi 2006). A driving factor behind this problem is the challenge of binding cellulose (Lu et al. 1998; Clemons 2002), the primary organic component of wood and the most abundant on earth, with other materials thus requiring matrices such as phenolic and formaldehyde resins. We approached the development of our material process by prioritizing its environmental characteristics, its potential for being used for additive manufacturing processes and then study its mechanical properties and potential applications.

2. Project Overview

The project is comprised of multiple research tasks: Material composition design and analysis, where we investigated various matrices from organic origin, selected a bonding agent which has been traditionally used in the fabrication of musical instruments and art restoration, performed testing for material mixing ratios, shear strength, temperature control, flow rate and curing time; Design and development of the electromechanical tools for 3D printing based on extrusion, integrated the end-effector with an industrial robotic system for motion control; and Investigated the special characteristics of fabricating extruded wood composite materials in terms of geometric limitations, machine motion control and instructions via computation (figure 1).



Figure 1. Overview of Process: From Material Experimentation to Robotic Extrusion.

3. Material Properties

Timber has been used as a naturally sourced, renewable, low embodied energy (Falk 2010) material with rich history in architecture, engineering and construction (Deplazes 2005; Ross et al. 2009). In its natural solid state, it has anisotropic properties derived from the composition of the grain, which allows it to be both structurally sound yet unpredictable at the same time (Wiedenhoeft 2010). Wood is light and strong, its compressive and tensile strength lies in the organization and build-up of fibres, composed of lignin and long chains of cellulose (Kretchmann 2010). We are able to harness similar qualities while manipulating the material density and mechanical properties by breaking down wood into fibres or particles.

Plastic wood composites is the broad family of engineered materials comprised of short timber fibres or wood particles bonded with a thermoplastic or thermoset matrix (Frihart & Hunt 2010). The main objective of those materials is to overcome the deficiencies of natural wood towards mechanical predictability and weathering (Stark et al. 2010). The environmental impact of those materials is dominated by the characteristics of the matrix in which thermosets perform worst, followed by thermoplastics, followed by bioplastics (Schwarzkopf & Burnard 2016).

The intent for our material design was guided by the desire to achieve 3D-printed wood, a material that is traditionally formed through subtractive fabrication processes, and to explore the potential of an environmentally more benign product than polymer wood plastics. The material we are developing is a particulate composite comprised of saw dust filler, an industrial by-product of timber processing also used in particle boards. The use of wood particles, though mechanically inferior to short fibres, was guided by the need for consistent flow in extrusion process. We experimented with various bonding agents and focused on the organic adhesives which are also by-products of industrial processes. The objective of the first phase of the material study was to determine the appropriate composition of material components for controlling fabrication such as mixing volume consistency, phase separation, viscosity, temperature, flow rate, curing time and mold growth before we even begin understanding mechanical characteristics which is planned for the second phase of the project.

We conducted tests with various natural binders exhibiting gelatinous properties to determine the most suitable sample. Starch is a polysaccharide derived from plants with adhesive properties which can be controlled by water solution and has been used for 3D-printing (Lam et al. 2002). Rosin gum resin is a natural low molecular weight polymer extracted from pine trees with thermoplastic properties. It is used as adhesive, food additive and generic tackifying agent for inks, rubbers and fluxes (Sivestre & Gandini 2011). Fish glue, derived from the skin and bones of fish is an effective binder for paper but is also applied to wood musical instruments. Hide glue, obtained from animal hide, is a thermoplastic binder that is used for woodworking and in musical instruments. Polyvinyl acetate, (PVA) also known as white or carpenter's glue, is biodegradable despite being derived from petrochemical processes (Chiellini et al. 2003). It is also effective in binding porous natural materials such as paper and wood. A comparison of their various properties is documented in figure 2.

As shown in figure 3 below, preliminary testing with those adhesive products using an Instron universal testing machine showed that even though PVA glue exhibited the highest shear strength out of all others products, both hide and fish glue were close. Starch was substantially weaker and rosin gum test samples failed completely perhaps due to wrong application. Nevertheless, the ability to achieve encouraging results with animal processing adhesive by-products motivated further exploration towards properties related to the intended use of extrusions for 3D-printing.

Glue	Density	Cost	Flow Rate	Bond Strength	Setting Time (without wood)	Temperature Control
	cm3/s	USD/g	cm3/s	N	min	°C
PVA	1.2	2.36	0.6	1925	15	NA
Starch	1.21	0.21	0.83	[illegible]	25	> 100
Rosin	1.2	[illegible]	0	[illegible]	[illegible]	70 - 100
Fish Glue	1	4.55	0.35	1670	10	NA
Hide Glue	1.08	4	0.06	1315	20	40-70

Glue Mix	Max Wood to mix for % (g)	Ease of Mix	Ease of Extrusion	Self Adhesion	Reversibility
PVA	40	High	High	Mid	With Water/Heat
Starch	[illegible]	Mid	[illegible]	[illegible]	[illegible]
Rosin	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fish Glue	18	[illegible]	[illegible]	[illegible]	With Water
Hide Glue	10 - 15	High	Mid	High	With Heat

Favourable
Fair
Unfavourable

Figure 2. Properties of Different Glues and Glue Mixtures.

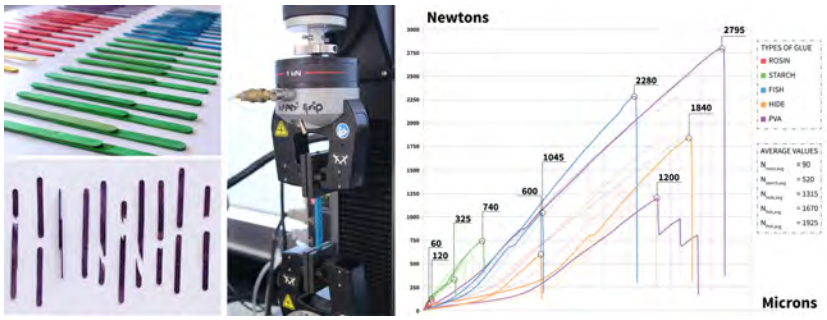


Figure 3. Testing Bond Strength of Glues using Instron Universal Testing Machine.

Viscosity is a rheological property examined for conveying and depositing materials but it is very difficult and expensive to measure accurately (Brummer 2006). As the viscosity of our materials are higher than fluids like paints and oils, we devised a method similar to the Zahn Cup viscosity measurement which is also indicative of the flowrate of the material passing through a hole at the bottom of the cup (Patton 1979; ASTM D4212 2005). Hence we designed a setup by which a finite amount of material is extruded via a syringe with a constant weight applied. While this approach is rather bespoke it allowed us to replicate tests and pin point range of acceptable compositions.

For each matrix we qualitatively evaluated its ability combine with wood dust to determine the maximum amount added while maintaining similar viscosities. Not all the binders combined well with wood sawdust. Due to high percentage of water in PVA and starch glue the mixture did not evenly mix and separated easily from the wood, leaving a stiff and un-extrudable compound. Rosin gum was difficult to emulsify with sawdust even with the use of solvents. Fish glue had increasing difficulty of mixing with sawdust and its working time was limited as upon contact it became extremely tacky. Hide glue mixed with sawdust had reasonable working time before it completely cooled and hardened. Overall, hide glue had the most favourable characteristics particularly for its ability to harden

by temperature control. This is an advantage for 3D-printing as it is desirable for beads to solidify as fast as possible in order to allow stacking of layers. The consistency and flow of the wood composite could be adjusted with addition of water, as hide-glue is water soluble; as such we continued to fine-tune the constituent mix ratios. Mixtures became smoother, uniform, less viscous and easier to extrude with higher proportions of binder and water but slower to cure and more difficult to stack. Mixtures with higher proportions of sawdust had rougher texture, were more difficult to extrude but also deformed more by curling as the material hardened.

Water loss via evaporation from the composite caused shrinkage in the samples. To determine the amount of shrinkage, we set up tests, measured and computed the differences in size of the samples, as defined by the average of two lengths of the square samples (figure 4). We prepared samples of 2mm, 4mm and 6mm thicknesses to verify if the effects of exposed surface area affected the rate of shrinkage. In general, the samples shrunk and stabilised at 13.7% after a period of 10 days. We observed that 2mm samples decreased in size at a much faster rate than the thicker samples, due to warping. However, upon applying heat via a heat gun and some pressure to un-warp the samples (on day 10), we noticed that the samples had only shrunk to an average of 11.2%, with a much smaller deviation range.

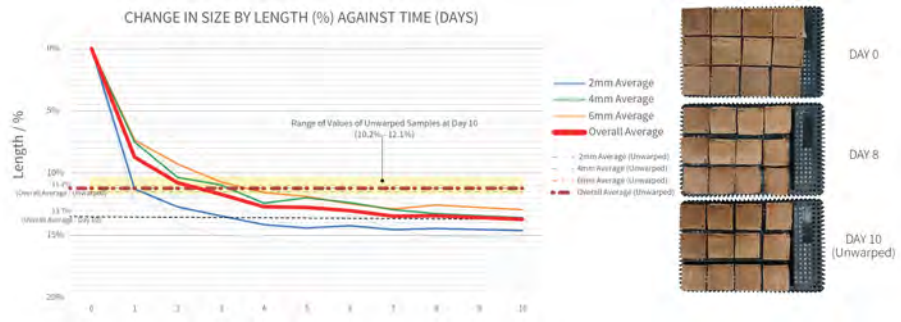


Figure 4. Shrinkage Results and Samples.

Visually, high matrix compositions failed to yield a wood-like qualities and took up the appearance of the binder instead. At higher proportions of wood sawdust, the mixture had more familiar aesthetic due to exposed grain. Unlike natural wood the samples exhibited waxy sheen and emitted a characteristic for hide-glue but not unpleasant odor that becomes less noticeable as the material cures. In order to experiment with the visual properties of a large scale product, as well as to test the machinability and finishing quality of the cured mixture, we cast a stool prototype using the sawdust-hide glue compound (figure 5). The prototype also allowed testing of the extent to which a large volume-mixture would warp during curing.



Figure 5. Cast Prototype of Stool Product to Evaluate Visual Properties and Machinability.

4. Tool Building

Given the high viscosity of the material and large pressure required to drive it through a small diameter nozzle, we adopted the auger screw design. An auger or Archimedean screw mechanism moves material forward using a captive rotating helix within a cylinder transporting materials from liquids to solids such as grains. As the wood composite material is much more viscous than water, there was a need to create an airtight system to ensure continuous positive displacement and prevent backflow against gravity and internal pressure built up. The additional benefit of the auger screw design in comparison to reciprocating pump with a solenoid flow control system is that it ensures pulsation free bead extrusion with capability of flow reversal.

We approached tool building starting from tools operated by hand and studying their effectiveness before moving towards an electromechanical system (figure 6). The early tool prototypes were used for studying the process of extrusion and finding a suitable material consistency. We used manual extrusion methods, employing squeeze bottles, syringes and simple augers. Next we developed iterations of the auger system that mounted onto the 6-axis robotic arm. The drive system is based on a lightweight, high gear ratio servo motor controlled via serial communications using an Arduino microcontroller. The mechanical parts were prototyped by 3D-printing. The total weight of the end effector was kept at minimum to allow more material to be loaded without interfering with the payload limitations of the robot. In addition, the effector was designed such that it is easily disassembled for cleaning. An injection port was also incorporated into the final design for externally refilling the system with material. The plastic material of the 3D-printed parts was also beneficial as a thermal insulator for retaining material temperature about 50°C where the material exhibits good extrudability.

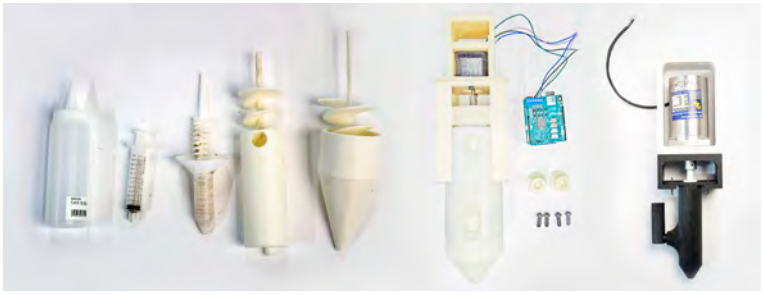


Figure 6. Tool Iterations from Hand Tools to Electromechanical System.

5. Robotic Fabrication

We integrated the extruder in a Universal 6-axis robot system with 10Kg payload (figure 7). This machine was chosen as a prototyping tool, because it is essentially a flexible CNC machine that can provide the positional control required for three-dimensional material extrusion. For our experiments, we restricted of the machine to 3-axis movement in order to simplify the extrusion process.

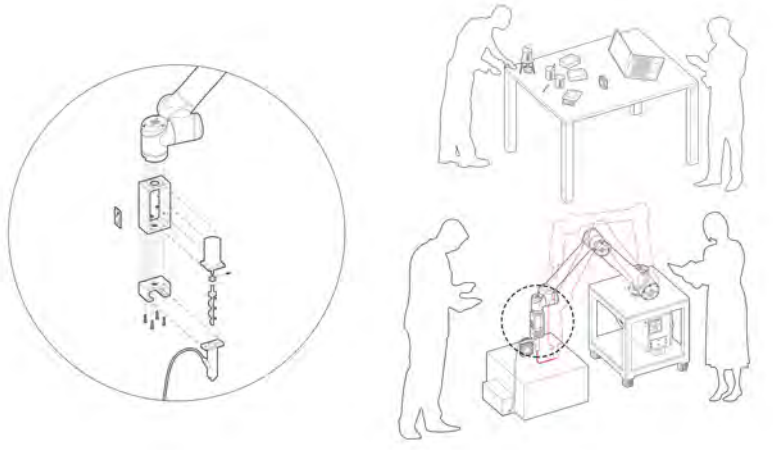


Figure 7. Tool Assembly and Robotic Setup.

The nozzle TCP follows a sequence of coordinate systems generated from machine paths created in Rhinoceros/Grasshopper, converted to machine code and transmitted to the robot controller using the Jeneratiff digital design and fabrication library (figure 8). Additional components for motion control were created using the C# programming language. The designs tested follow the conventional CAD/CAM for CNC and 3D-printing approach converting geometry to machine paths and the machine code in principle. However, as many parameters are under investigation, we approached design generation backwards from motion to form.

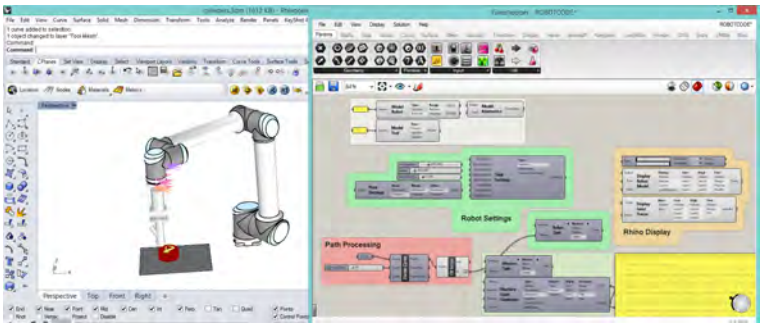


Figure 8. Motion planning and Translation to Robot Code using Jeneratiff on Grasshopper.

As such we tested rather simple planar shapes for calibrating robot motion and material flow speeds and spiral geometries for evaluating the vertical material behaviour (figure 9). For accessing the overhang behaviour and ensure stability of wall thicknesses, we employed a protruding multi offset layer strategy which is typical in filament deposition 3D-printing; also used for ensuring best exterior finish as opposed to interior. A more robust strategy left as future exercise is the development of internal webbing using material lattices which is also a common strategy in most 3D printing processes. We tested two methods for vertical motion transition between layers, namely u-turn and cross over, as well as various vertical step over ratios such that the extruder compresses material to increase adhesion between layers. Due to slow curing time which restricted the speed of extrusion and resulted to collapsed walls we used a fan to convectively cool the prints such that we could build faster and higher.

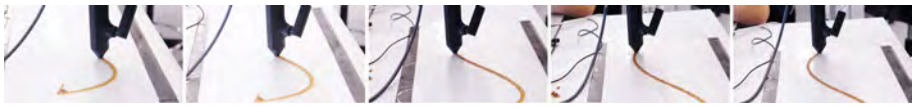


Figure 9. Testing Robotic Motion with Material Extrusion.

6. Conclusions

We presented the initial steps in the development of a wood composite 3D-printing process highlighting the multitude of complex parameters required for successful production of sustainable products using traditional material and contemporary digital fabrication processes. There is a lot more work required to fully understand the material in both its mechanical as well as its aesthetic properties before we can even begin the design of products. Moving directly into building construction is even more challenging as it will require to address issues such as behaviour against fire hazards, thermal insulation performance and long term resistance against weathering.

Nevertheless, inspired by the current progress made we can envision some potential applications. Our matrix possesses exceptional properties such as its ther-

moplastic behaviour and self-adhesion. Those are key characteristics for its use in artwork and musical instrument repair. It is thus potentially interesting to investigate both additive repair and even full reconstruction of architectural ornamentation for heritage buildings. In past studies (Dritsas & Yeo 2013) we witnessed the challenges in periodic restoration of timber temples which is dependent in an art and craft progressively vanishing. With careful consideration a 3D-printing process may be a valuable tool for built heritage conservation.

Using 3D-printing process may also allow us to exactly revisit those traditional forms of wood working (Kaijima et al. 2016) deploying purely material and geometry for construction without use of nails, screws and extraneous fasteners (Seike 1977). Thus a contemporary application relevant to the resurrection of timber as building material supported by the need for sustainable design and construction processes is in the domain of timber joinery. The process of 3D-printing is exactly relevant because connection between elements such as posts and beams are the most complex to design and fabricate. We look forward for further design, experimentation and prototyping that will help bring some of those ideas into practice.

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FURNITURE DESIGN USING CUSTOM-OPTIMISED STRUCTURAL NODES

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Abstract. Additive manufacturing techniques and materials have evolved rapidly during the last decade. Applications in architecture, engineering and construction are getting more attention as 3D printing is trying to find its place in the industry. Due to high material prices for metal 3d printing and in-homogenous material behaviour in printed plastic, 3D printing has not yet had a very significant impact at the scale of buildings. Limitations on scale, cost, and structural performance have also hindered the advancement of the technology and research up to this point. The research presented here takes a case study for the application of 3D printing at a furniture scale based on a novel custom optimisation approach for structural nodes. Through the concentration of non-standard geometry on the highly complex custom optimised nodes, 3D printers at industrial product scale could be used for the additive manufacture of the structural nodes. This research presents a design strategy with a digital process chain using parametric modeling, virtual prototyping, structural simulation, custom optimisation and additive CAD/CAM for a digital workflow from design to production. Consequently, the digital process chain for the development of structural nodes was closed in a holistic manner at a suitable scale.

Keywords. Digital fabrication; node optimisation; structural performance; 3D printing; carbon fibre.

1. Introduction

Recent developments in the field of computational architecture and new developments in fabrication technologies reveal many possibilities to generate complex designs with a high degree of visual differentiation. Increasing demand for intricate geometries and mass-customized building components opens the opportunity

for individualized expression of structures in architectural design processes. Over recent years, new applications of additive fabrication for the design of structural components were developed and custom-optimisation of structural nodes were tested on a scale pavilion to show first glimpses at the design potential of these design methodologies (Williams et al. 2015; Prohasky et al. 2015; O'Donnell et al. 2015). Innovation of structural component design, developed in the research presented here, uses a novel custom optimisation approach based on cross section optimisation for the improvement of the structural performance during different design iterations.

During the research project, a design process based on a closed digital process chain for custom optimized structural nodes was explored and implemented on a furniture scale. After development of a concept design, a virtual prototype of the design was developed to review the aesthetic appearance and the feasibility of the fabrication system for construction. Multiple iterations of optimisation of the structural system were carried out on multiple scales to reduce the material needed for the structural nodes. As a result, a significant reduction in cost and fabrication time were achieved.

The close collaboration with the structural engineers during the design process in design development allowed short iteration cycles and lead to a stream lined design process. In the meantime a collaborative parametric model was build in the design team, so that structural as well as design input was reflected in the model simultaneously. Above all, the constant communication during the design process created the potential for novelty and innovation during the design process, and led to a design outcome with a holistic aesthetic appearance, material reduction through the custom optimisation of the structural nodes, and a reflective approach to fabrication constraints during the design process.

2. Background and Critical Review

Recent developments in the field of computational architecture and new developments in fabrication technologies revealed many possibilites to generate complex designs with a high degree of visual differentiation. Increasing demand for intricate geometries and mass-customized building components opens the opportunity for individualized expression of structures in architectural design processes. Over recent years, new applications of additive fabrication for the design of structural components were developed and custom-optimisation of structural nodes were tested at a pavilion scale to show first glimpses at the design potential of these design methodologies (Williams et al. 2015; Prohasky et al. 2015; O'Donnell et al. 2015). Innovation of structural component design, developed in the presented research, uses a novel custom optimisation approach based on cross section optimisation for the improvement of the structural performance during different design iterations. Here following observations have been made:

- MATERIALS: Whereas ABS and/or PLA prints do not have the structural integrity needed in the construction industry, printing in metal as outlined in the research by Galjaard et al. (2014) which would fulfil the structural requirement is currently still an expensive undertaking. Projects such as the ones by

Williams et al. (2015) rely on 3D printers on an industrial scale and the cost of the use of such equipment is still high compared to conventional manufacturing technology for structural nodes like on site welding or steel casting. Currently most 3D printers are in a table top format. This is the case for popular types such as Makerbots, Flash Forge or UP printers using ABS and/or PLA as well as metal and other substrate printers. Particularly cost effective are the products that use plastics for the additive manufacturing process. As a consequence, the fabrication process for the structural nodes in the presented research used conventional table top printers for PLA.

- TOOL DIMENSIONS: Any structural node is limited to the size of the printer. The application of a custom optimisation process for structural nodes on the furniture scale offers the possibility to test the use of custom optimized nodes in a final product and therefore provides first insights in a design and fabrication process suitable for commercial use. Commercial activities in future additive manufacturing scenarios attribute great value to product customisation (Bertling & Rommel 2016), as attractivity of Direct Digital Manufacturing increased (Gibson et al. 2015).
- EVALUATION OF OUTCOMES: Before additive manufacturing can be introduced on an industrial scale to construction processes, adequate material testing, norming and issuing of code for the application of these fabrication process need to take place. In contrast, the experimentation on the furniture scale leads directly to potentially commercialisable design outcomes. This consideration points towards the potential for future development, while recognizing the current limitations for additive manufacturing (Naboni & Paoletti 2015).

Thus one can observe that even additive manufacturing has continuously advanced over the last decade with most 3D printers still have their limitations when it comes to printing custom-optimised structural components. This is the case for currently used materials and their associated techniques. Thus 3D printing has not yet had a very significant impact at the scale of buildings other then a few experimental projects such as the one by Williams et al. (2013), O'Donnell et al. (2015) or Galjaard et al. (2014) to name but a few. As argued above, scale, cost and structural performance have also hindered the advancement up to this point. Based on these observations, the research presented here describes experiments of an application on a furniture scale along with the presentation of a novel approach to custom optimisation of structural nodes.

3. Methodology

The researchers describe a design strategy for custom optimized structural nodes in the context of furniture design along with a novel approach to custom optimisation of structural nodes based on cross section optimisation. In summary, the following iterative design research methodology was used to design and fabricate:

- Concept design based on sound and water waves as reaction on site
- Virtual prototype of the preliminary table design
- Micro-scale optimisation of structural nodes
- Macro-scale optimisation of the structural system

- Multi-scale structural model for custom-optimisation of structural nodes
- Fabrication of the Opera Bar Table as a final product

Here a bar table was designed that used Karamba for optimisation of the overall structure and structural nodes. Designed for a music event, the preliminary design sketch mimicked sound waves as a first form iteration. The resulting NURBS surface was broken down into triangles in order to use timber members for construction. Each beam was connected to a node with a minimum of two and a maximum of six beams connected at specific points. The nodes were designed via La Placian smoothing based on the results of the cross section optimisation process. With this initial design approach, multiple optimisation cycles took place during the design development.

4. Case Study - Sydney Opera Bar Table

The Sydney Opera House (1959 - 1965) in particular the constructions of the shells of the Opera House challenged architects, engineers and construction firms at the time and "the enormous challenges in construction demanded pioneering applications and many new materials as well as building and engineering practices" (Sydney Opera House, 2016).

DESIGN PROCESS: Bachelor students of the Computational Design degree at the Faculty Built Environment / University of New South Wales, Sydney were challenged with the question: "What would a contemporary equivalent in design and construction that 'demand[s]ed pioneering applications and many new materials as well as building and engineering practices' in a way similar to the Sydney Opera House (2016) description in its historic outline".



Figure 1. Concept design based on sound and water waves (left three bubbles); optimisation of design sketch in Karamba (middle three bubbles); and detailed view of preliminary table design (right bubble) (c) Emily Leung.

Figure 1 shows the selected design concept developed in the two week Karamba workshop. The design at this stage existed as a preliminary design that had been, in a first iteration, optimised in Karamba. Still the design of the nodes and the overall structure needed further optimisation iteration cycles to meet the fabrication constraints given by the additive manufacturing process.

Instead of designing an opera house as such, and dealing with spatial and or-

ganisational matters the students were asked to test and explore the challenge on a furniture piece. The motivation for the design of a bar table came from being commissioned by Opera Australia to develop a VIP area centre piece for their upcoming opera 'The eight wonder' that had the design of the opera house as theme. Each student used the design challenge to learn the Karamba plug-in for Robert McNeel & Associates' Grasshopper® to design a table that somehow mimicked ideas and concepts of the Sydney Opera and optimised the structural system.

OPTIMISATION ITERATIONS: During the development of the case study, multiple iterations for the structural simulation and optimisation were carried out. The experimental setup and the results of the design process are provided in the next section to provide knowledge about the development of the overall and component geometry.

Micro-scale optimisation of structural nodes - The design of the structural nodes was informed by structural simulation during the development of virtual prototypes for performance evaluation. As the results of the simulation were based on a finite elements solver calculated by using Robert McNeel & Associates' Grasshopper® and the Karamba plug-in, the geometry was generated directly in the parametric model. A novel custom optimisation approach was developed inside the parametric design environment. Based on the generative process for the generation of the structural nodes, different node sizes were necessary to provide all the fabrication data inside the parametric model. The structural system was divided into the structural nodes and the beams that represented the timber members through the subdivision of the connectivity diagram with spheres. In the next step the beams were sorted based on their topological adjacency to the positions of the structural nodes, so that a sorted list provided the basis for the assigment of materials and the generation of the node geometries.

Feeding the calculation results of the cross section optimisation into the Exoskeleton plug-in to generate a mesh as the basis for the Laplacian smoothing allowed a high level of variety in the node design, while a coherent design language was developed. This methodology has a number of advantages, such as the concentration of the structural complexity in the geometry of the nodes that provides a focus for the geometrical optimisation on the structural node. Another advantage is the small computational costs of a cross sectional optimisation as compared to other optimisation approaches that have been used in that context. The generation of all the node geometries was handled in one coherent parametric model that could update in a relatively small amount of time after changes were introduced.

The results of the optimisation process described are shown in figure 2 and figure 3 (left image). At this stage rather large nodes were generated, which did not satisfy the designer's expectations about the printing time and use of material, while also violating fabrication constraints. Many of those node designs would have needed to be divided into several parts for the additive manufacturing process, therefore adding an additional step to the construction process.

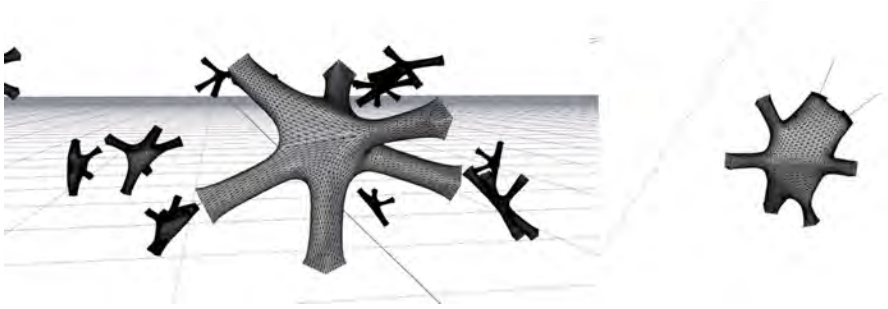


Figure 2. Optimised nodes as used in final design (left) and single node when only optimising node but not structure - hence a 'lumpy and large' outcome (right).

Macro-scale optimisation of the structural system - After a first iteration of the custom optimisation proces for the structural nodes of the furniture design, the overall shape of the table was assessed for design optimisation by the structural engineer. During this process a symmetric approach for the structural design was developed and applied to the structural system to provide better balanced table based on two 'shells' that form, preventing a potential tipping over when on site. Another step to improve the performance on the macro-scale of the structural system was the relaxation of the positions of the nodes on the design surface, so that an even distribution of the nodes was reached.

Through this process the length of the timber members was averaged, thereby balancing the utilisation of the structural members in reaction to the need of using the same cross section of the structural members over the whole structure. Here the total number of nodes was reduced as well as the size of each node offering improvements in cost and fabrication time. As a result, the node sizes were significantly reduced and a more coherent expression of the structural nodes were achieved as improvement to the overall design (compare changes in structural layout in figure 3).

The parametric model that incorporated structural simulation and optimisation in the design model, based on an ongoing collaborative design approach between architects and engineers, was adjusted to incorporate the changes in the overall geometry. In addition, the material properties for the structure were reviewed to ensure the structural feasability of the final product. Further improvement was achieved by changing the material for the tabletop from glass to acrylic, resulting in a significant reduction in dead load of the structure.

Multi-scale structural model for custom-optimising of structural nodes - In another iteration of the optimisation process, the whole system - the beams in combination with the custom optimised nodes - was simulated to generate another set of structural nodes that met the fabrication constraints. Two load cases were introduced to reflect the impact of gravity and the total load live load of 100 kg/sqm that deemed to be appropriate for the use of the table in a bar space (final result in figure 3 right).



Figure 3. Screenshot of designed table with node optimisation only (left) and node and structural optimisation (right).

This last iteration applied in the design process was successful in reducing the size of the nodes to the print bed of the Flash Forge 3D printers used in order to meet the upcoming fabrication and handover-to-client deadlines.

FABRICATION AND ASSEMBLY: Following multiple optimisation iterations and the 3D printing of the 32 structural nodes, all connecting timber members were cut to size and the team assembled the table. The connection between 3D printed node and timber member was facilitated through the use of the FESTO Domino system as it created an invisible connection joint (see figure 4 and 5).



Figure 4. 3D printed nodes (left); timber members (middle); and first assembled connection (right).

The whole construction process took place using unskilled labour, which would allow the application of the proposed design strategy for development of a commercial furniture system that would leave the assembly of the furniture to the customer. For this application, the tectonic detailing would need to be reworked, as it only incorporates a gap for the insertion of the dowel at this stage.

Only one node was split in two parts for the additive manufacturing process. This allowed the researchers to evaluate the feasibility of gluing and screwing of the node as part of the assembly process. During the process, various glues were tested and a standard two-component glue used in during construction of the table. In the following all 32 nodes were printed and connected to beams to build a table with a 2.4*1.2 meter surface. The fabrication and construction process are described in greater detail in the next section of the paper.

5. Conclusions

This research has investigated the design process for custom optimisation of structural node for an application of such a system on a furniture scale and successfully introduced a novel custom optimisation method based on cross section optimisation. As a result, structural integrity, fabrication time and cost were significantly reduced during the design process. As a full scale application of the design process, the research provides first insights in the application of custom optimisation of structural nodes for the development of a marketable product. All of these aspects will be expanded on in the following conclusions.

CUSTOM OPTIMISATION OF STRUCTURAL NODES: In general the results show that the developed approach to custom optimisation of structural nodes based on cross section optimisation and La Placian smoothing can be used successfully to quickly iterate over multiple design options, as the process is computationally cheap. Another advantage of this process is the simulation of the whole structural in one coherent parametric model with different materials. In this respect, the process could easily be extended towards the use of different cross sections for the structural members and multiple structural materials.

At this point the structure has only been tested in a virtual model and through a rudimentary testing process in situ. In the physical testing the research team loaded the table with gym weights and sandbags. As these tests were made prior to handing over the table to the client we naturally did not go to the full loading of 100kg/sqm but stopped at 80kg/sqm.

FABRICATION TIME AND COST: The design methodology based on node optimisation and additive manufacturing has been a quick and cheap process for the generation of a complex design outcome that could be handled by a small design team. Hence we argue that the objective of developing a quick and cheap method of fabrication and construction has been achieved. The overall costs for the prints were under US$ 150 (a total of 4 rolls were used for the process), the printing times varied between 12 and 23 hours. Due to having six Flash Forge Printers available the total print could be completed in about a week. All nodes were printed solid in order to give them their maximal strength. Using ‘tree structures’ as support the amount of support material needed during manufacturing was reduced to a minimum as well, also reducing time required in cleaning the nodes.

The research in the construction process was limited in several ways. Mainly time and resource constraints needed to be accommodated. More research is needed in further optimisation of the tectonic details inside the parametric model to accommodate easier assembly without the use of glue, further exploiting the design potential provided through additive manufacturing technology. Although the study did not explore multiple approaches to the design of the assembly system, it tested the one (figure 6) in great detail and explored the potential application of gluing and screwing of nodes to accommodate limitations in meeting the fabrication constraints.

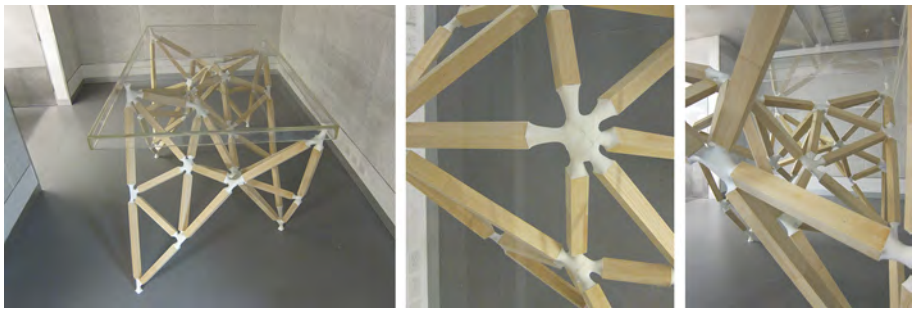


Figure 5. Table assembled (left); detail view nodes (middle); and perspective table with several nodes (right).

Only one node was split in two parts for the additive manufacturing process, which allowed the researchers to evaluate the feasibility of gluing and screwing of the node as part of the assembly process. During the process various glues were tested and a standard two-component glue was used in the construction of the table. Subsequently, all 32 nodes were printed and connected to beams to build a table with a 2.4*1.2 meter surface.

FURNITURE DESIGN APPLICATION: The findings add to our understanding of the development of furniture with complex topologies and geometries through the use use of structural optimisation methods. We are aware of the fact that the introduction of this level of complexity into furniture design is open to criticism, but want to point towards the potential application of the design strategy for the design of furniture systems for mass customisation. These might be used to adjust this particular furniture design to individual taste through interactive methods.

Finally, the furniture scale seems to be the a well-chosen testing ground for the application of custom optimisation of structural nodes on a product scale as a vehicle for the exploration of commercial applications of the design strategy.

6. Next Steps and Future Research

The next iteration of the research will target the use of a robot arm for the wrapping of structural nodes with carbon fibre to introduce additional stiffness to the component design and enhance the capabilities of the structural node to perform under a variety of loads, especially under outdoor conditions. This composite approach to the fabrication of structural nodes will provide a new materiality for the use of structural nodes in the context of building construction, and test the method on a physical prototype to explore the associated fabrication constraints. Another step of the research project will be the evaluation of the material properties of the hybrid structure combining PLA and carbon fibre in the structural node in collaboration with material scientists and engineers. This paper provides a starting point for the development of novel optimisation methods in the context of mass customisation of structural components and associated fabrication methods. The nodes were designed via La Placian smoothing based on cross section optimisation instead of

using a topological optimisation approach, as the latter would result in geometry too complex for a carbon fibre laying robot arm to achieve a feasible outcome of the fabrication process.

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RANDOMNESS IN ROBOTICALLY FABRICATED MICRO-ACOUSTIC PATTERNS

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Abstract. Randomness can introduce degrees of variation as part of a highly controlled design process, which can be of particular significance in the context of acoustic performance in architecture. This paper presents research into robotic fabrication of surfaces with acoustic micro-patterns that can change the acoustic response of space. It explores the design affordances for acoustically efficient 1:10 scale model prototypes, from parametric modeling to scale model production to physical evaluation. Acoustic reflective properties of surface patterns are investigated for scattering coefficients, in order to derive statistical data on acoustic properties of these surfaces, and to deduce design rules. The robotic subtractive process particularly invests variations and disturbances to originally coded fabrication sequences that lead to different pattern outcomes. Changes to protocols and workflows change the equations of design through shuffling of multiple criteria: from multiple sequences in a production process to intuitive impacts of the designer on a preset tooling and workpath; from computational design code to acoustic effect.

Keywords. Robotic subtractive manufacturing; micro-acoustic patterns; sound scattering; design thinking.

1. Introduction

In room acoustics, principal measurements usually refer to the clarity of sound or speech intelligibility, reverberation, and loudness. As Burry (2010) has pointed out, acoustic optimization is a qualitative process, despite the contribution of measurements and qualitative systems. In architectural acoustics, the overall geometry of spaces, and the specific reflective qualities of surfaces (material hardness, patterns) further contribute to a sound experience. Acoustic experiences can be shaped via control of complex curved spaces (Reinhardt et al 2012, 2014), or the introduction of micro-acoustic patterns (Peters et al 2010, 2011, Burry 2012, Reinhardt et al 2016). Architecture contributes to varied sound experiences when surfaces are differentiated, such as micro-acoustic zones where acoustic experience

differs from the surrounding area. Aural environments directly and critically relate to human affective responses, impacting on a 'sense of privacy, socialization, and territoriality' (Blesser and Salter 2007). Addressing aspects of microsound conditions is a way to approach environmental building performance on a conceptual, programmatic and material level, which allows the rethinking of architectural space as a sound-ecosystem (Burry 2010). Through combined physical and biological components of an environment, a network of relations between architectural envelope, surface conditions, materials and advanced manufacturing processes can address acoustic performance of spaces.

1.1. RANDOMNESS

Current computational design approaches apply chaotic or unpredictable surface patterns commonly in aesthetic developments. As a concept of variation, randomness can be part of a highly controlled design process (Burry 2014), which can be of particular significance in the context of acoustic performance in architecture. Surfaces deliver better acoustic scattering performance when based on aperiodicity. As has been argued, beyond stochastic approaches to optimisation (through finding the fittest solutions for a combination of variables), randomness can contribute to a greater range of diversity in architectural surfaces, and their acoustic performance understood statistically. The introduction of a degree of random variation in the surface has the potential to increase the frequency range of effective scattering, or absorption of sound - depending on the depth of valleys, and diversity of the pattern. This paper reports on research in progress; an empirical study of the relationship between robotically fabricated surfaces and acoustic scattering. It extends previous research into robotic fabrication of micro-acoustic patterns, (Reinhardt, Cabrera et al 2016) such as the relationship between the depth range of the relief in the surface pattern and the frequency range for high scattering values. The aim of the present study is to apply randomness as intuitive intervention in the fabrication phase. The research generates many different algorithmically derived patterns, and evaluates them in terms of digital modelling; advanced manufacturing of surfaces in robotic fabrication, and consecutive testing - so that general trends can potentially be determined (figure 1).

1.2. PHYSICAL FORM AND ACOUSTIC SCATTERING

The scattering of sound when reflected by a surface can be a desirable characteristic in the acoustic treatment of spaces (Cox and D'Antonio 2009). Scattering can ameliorate characteristics of a room's sound that are often undesirable, such as discretely audible echoes, flutter echoes, coloration due to comb filtering, spatial focusing, and discrete tonal resonances. This is of particular importance when it would be undesirable to remove the sound energy from the room by absorption. Scattering is also used to enhance the spatial impression of the sound in critical listening spaces such as auditoria or sound studios (Schroeder 1979).



Figure 1. Robotic cut with KUKA KR 6, pattern series, and acoustic testing in reverberant box.

In contrast to repetitive, homogenous, or periodic surface expressions, scattering is commonly achieved by variation: varying the angles and depths of a surface, and so typically uses visually interesting architectural forms. Relationships between the sound wavelength and the size of the undulations or roughness are complicated, and since the wavelengths of audible sound span a wide range and are significantly large on an architectural scale (ranging from 17 mm to 17 m), the scattering behavior of surfaces is frequency dependent. Longer wavelengths correspond to lower frequencies, and so it can be particularly difficult to achieve low frequency scattering with practical surface designs. Scattering at high frequencies may be achieved with relatively shallow surface modulation. Therefore, a common challenge in scattering surface design is to extend scattering to as low a frequency as possible for a given surface modulation depth. In addition, increasing surface roughness particularly through fine features is likely to increase its sound absorption. While precedents for scattering surfaces such as the quadratic residue diffuser (QRD, Schroeder 1979) commonly use square elements, scattering can also be achieved through random, pseudo-random, ad hoc or algorithmically designed modulated surfaces. Although the scattering performance of such is harder to predict than for established design techniques, incremental variations can be computationally controlled via well depth and well width. Recent approaches have further tested complex curved geometries, such as hyperbolic patterns applied over a curved surface (Peters, Burry, Williams, Davis 2013), or surface differentiation through Hexagon, Wave and Batten patterns (Peters Olesen 2010).

Yet with robotic fabrication, a larger design spectrum becomes accessible for non-periodic patterns that can be fabricated in single robotic machine motion, effectively changing acoustic concepts from singular wells to 'valleys. This research discusses robotic sound discs that modulate scattering surfaces (figure 2), where randomness was introduced to support criteria for difference in a) mathematically described generation as base code or DNA for various pattern studies); to the b) selection of disc area within the pattern topography; to c) fabrication with select hot-wire shapes for cut (v-shape, leaning square, u- and o-profiles; the d) relative depth of toolpath; and the e) control over script for robotic substractive cutting

as full or partial stage. In a subsequent acoustic evaluation, tendencies for sound scattering were tested, so that relationships between complex geometries, acoustic effects, and robotic fabrication can be better defined.

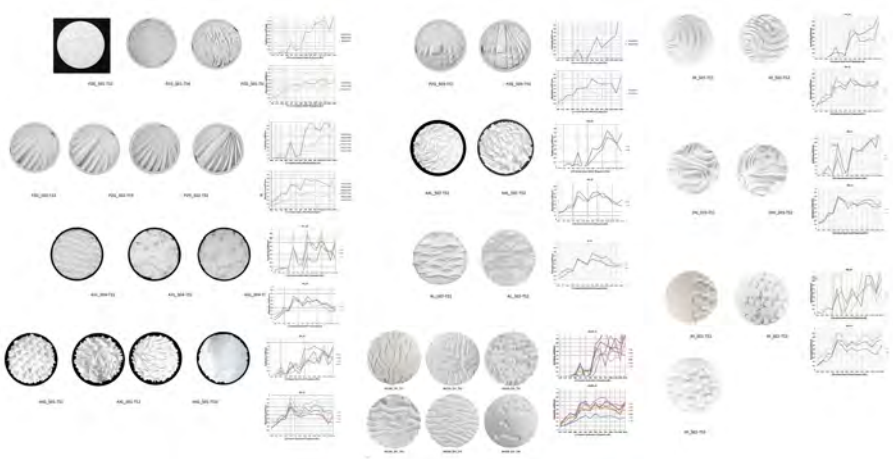


Figure 2. Exert of 35 sound discs with micro patterns, and resulting scattering and absorption performance.

2. Pattern Coding and Robotic Fabrication

As a shared geometry, circular disks were fabricated based on two standard equations that determine relative height and depth. These are a height ≥ 1/16th of diameter (Peters and Olesen 2010); and a depth of d < ó λ , in order to be effective for a certain frequency (Bonwetsch et al 2008). Following these dimensions, sound discs were first fabricated in EPS Styrofoam (a close-packed and non-directional material), with 310 mm diameter, 40mm material depth (with potential 19 mm surface depth). Each sound pattern integrated generalisation (percentage of depth in surface) combined with uniqueness (different executions of algorithms that result in unique appearance). A level of variation or randomness was introduced to avoid using a regular periodic pattern and maximize frequency spectrum for scattering; so Turing Patterns, L-Systems, Dynamic Flow or Agent behaviour were coded in GH Grasshopper, and simulated in KUKAprc (figure 3).

The study then used the advantage that six-axis robotic fabrication holds over CNC machining, which requires multiple step-downs with a 3-axis milling path. Robotic hot-wire cutting uses a single tooling line that determines the two sides of a valley, and cutting at angles significantly different to the surfaces' normal (Reinhardt et al 2016), which is optimal for fast patterning of surfaces. A hand-held hot wire cutter (THERMOCUT 12/E) was mounted on a KUKA KR 6 robot arm and equipped with varying bendable wire profiles of average depth of >10mm. Consequently, the robotic movement range and angle enabled fine details with short machining times and multiple valleys in surfaces as a result from directional robotic subtraction. The different wire profiles increased the design spectrum for fabrica-

tion of undercuts (which optimizes absorption performance). For direct intuitive changes, robot programs were partially executed across 3-4 discs, as opposed to precise micro-scale prototypes in CNC. In several test series (figure 4), robotic parameters creatively and intuitively varied, including: toolpath and defined angle of the subtractive tool; multiple passes along isocurve; the distance of end-effector to material surface; and the depth and surface angles of valleys variable along the curve.

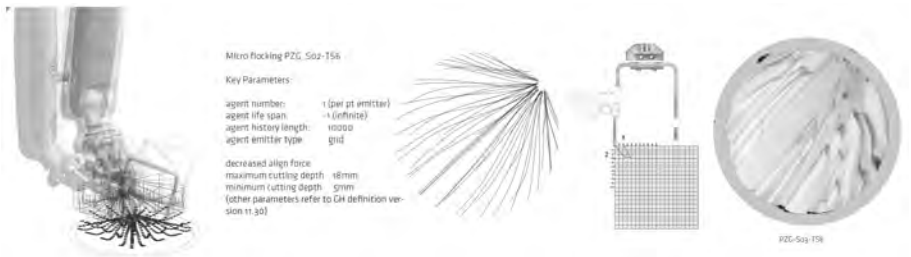


Figure 3. Exemplary phasing: robotic simulation, pattern DNA/code, wire shape, sound disc (PZG, Flocking Flowl, Guoliang Zhen, CodeToPro2016) .



Figure 4. Initial analogue testing (left, mid), and KUKA KR 6 workcell (right, CodeToPro2016, DMaF Team Watt and Masuda).

Four prototype series illustrate in the following a L- or Branching-System as departure point (figure 5). In MLDM-S1, branches were created by setting an area, populating it with a given number of points, and connecting all proximity points with lines. Number of branches correlated to points occupying the area, with continuous increase of lines when point numbers increase, resulting in denser branch populations. Robotic cutting applied a generic V-shape, resulting in a relative high percentage of remaining surface area due to widely set pattern. In MLDM-S2, variations included line depths (0mm to 20mm), higher branch density (more initial points), and relocation of tooling origin point. While the same wire profile

was maintained (V-shape), the non-rotational robotic arm movement, cutting in a single direction, results in different effective width of 'cutting line' and produced valley. In MLDM-S3, the original branching code was modified to introduce a directional flow so branches 'grow' towards the same direction. In addition, lines for this variable were disconnected, leading to an interrupted robotic toolpath (PointToPoint or PTP) where the robot arm reach a point, lift down, cut one line, and lift up again, and so forth. The wire profile was changed for this series (widened V-shape). In MLDM-S4, different stages of the overall robotic script were consecutively fabricated across 3-5 different discs. Robotic fabrication extends here randomness through motion control, tool-path angle and shape of end-effector.

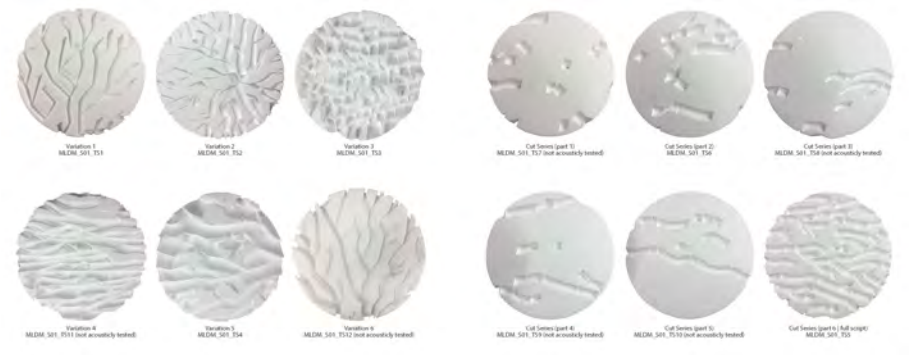


Figure 5. Prototype series based on generative design and robotic fabrication (MLDM, L-System Series, Michel Luis de Melo, CodeToPro2016).

3. Acoustic Measurements of Sound Discs

Resulting from variations in robotic trajectory, depth and sequence, the generated patterns were random, non-periodic and non-directional. In order to assess their sound behaviour, standard controlled tests for each 1:10 scale prototype were undertaken. Scattering coefficients and random incidence absorption coefficients of the discs were measured using a scale model reverberant room (here, a reverberant box with an internal volume of 0.284 m3, see figure 1). The measurement procedure was based on ISO 17497-1, with an inverse repeated sequence signal of 60s as effective measurement period (Stan et al. 2002). The sample was recessed to half its depth into a turntable, which was either still or rotating with a period of 60 s for full rotation. In order to calculate the scattering and absorption coefficients, the test signal was used to measure reverberation time of the box in four conditions: with sample, without sample, combined with the turntable still, and rotating. AARAE software (which is Matlab-hosted) was used for signal generation, playback and recording, processing and analysis (Cabrera et al. 2016). Reverberation time was calculated in 1/3-octave bands over the 1 kHz - 20 kHz.

3.1. ERRORS AND LIMITATIONS IN ACOUSTIC TESTING

Both sets of coefficients should have a value between 0 and 1. However, measurement prototypes can yield results beyond this range. In particular, the edge of the sample can have an unduly large effect on coefficients, sometimes yielding values greater than 1 - this is a very well-known phenomenon in absorption coefficient measurement. If a sample is highly absorptive, that is likely to reduce the precision of scattering coefficient measurements. The polystyrene material used for the samples is not particularly absorptive when smooth, but rough surface texture and fine cuts can substantially increase its sound absorption coefficient. At low frequencies, some absorption may come from the sound penetrating the material itself. Fine surface roughness is most likely to yield greatest absorption at high frequencies. In order to provide a succinct summary of the sets of coefficients, mean values over the 2 kHz -20 kHz range were calculated. Values below 2 kHz are likely to be less reliable (due to the lower modal density of the box at low frequencies) and are also of less interest for scattering given the scale of the discs (the wavelength of 2 kHz is 0.17 m). The centroid of scattering coefficient (or mean) was also used to provide an indicator of the distribution of scattering values over the eleven 1/3-octave bands. This was done following an equation where fn is the centre frequency of each band, xn is the value (scattering coefficient in this case), and n is the band index.

Centroid of scattering is of most interest when scattering coefficients are high, at least in some bands. Scattering is quite easily achieved in high frequency bands, and greater variation in surface depth is needed to achieve high scattering at lower frequency bands. Hence the centroid provides a succinct indicator of the extent to which the scattering extends across the frequency range (a high value indicates that scattering is mainly at high frequencies, while a lower value indicates extension to lower frequency bands). Scattering is of most interest when absorption is low. However, while the scattering coefficient values should translate to the same form using other materials and at other scales, the absorption coefficients are specific to the samples tested. If the discs were instead made from a smooth, hard and dense material, it is unlikely that such high absorption coefficients would have been measured. Similarly, if the discs were scaled (e.g. by increasing the linear dimension by a factor of 10), fine cuts would broaden, resulting in reduced sound absorption coefficients at the scaled frequencies. Usually the type of scattering measurement performed for this study assumes that the sample is a scale model, and if the envisaged scale was 1:10 then the 2-20 kHz measured range represents 200 - 2000 Hz, which covers much of the speech frequency range.

3.2. TESTING OF SAMPLES AND OVERALL COMPARISON

The mean scattering coefficient and centroid provide a quick summary of each disc (figure 6). Sample PZG-S02-TS6 showed the highest mean scattering coefficient of 0.63 with the centroid scattering frequency at around 10 kHz. It also had a relatively high absorption coefficient of around 0.65. Characteristic for this particular prototype are deep undercuts, and linear smooth surfaces. This led to the working hypothesis that larger area of smooth surfaces of varying angles potentially

increase scattering, and deeper valleys increase absorption. Deep undercuts both created a relative large amount of flat surface area, and deep valleys at the same time. This result will be subject to further evaluation, as is the ratio between size of the undercuts and certain frequency's wavelength, which require further investigation in regards to the scattering and absorption performance. As a preliminary result, the following tendencies were demonstrated: 1) as opposed to CNC machining, robotic manufacturing through spline curves offered a much larger scope for variability in the production of sound discs, due to easily accessible transfer of GH code to robotic machine code; 2) a maximum depth of valley could be continuously achieved across the surface (all samples, see); 3) as confirmed by acoustic testing, similar densities of valley patterns cause similar acoustic behavior, with simple robotic deposition of patterns on the surface (samples MLDM, AXL) ; 4) a periodic spatial design of surfaces produces a periodic scattering spectrum with regular visible peaks, whereas non-periodic pattern organisations tended to demonstrated a smoother curve for centroid of scattering coefficient (sample AXL); 5) very random patterns did not produce better scattering (PZG_T02); 6) general evaluations in regards to cut and removed material (percentage of waste) were easy to measure, but as estimated unlikely to be reliable, and thus could not yield significant results for further tendencies (all samples) as the most interesting result, from the same code but with a change of tool, a both scattering and absorption highly efficient surface could be produced through very few robotic tooling lines, and with a wire profile that generated an undercut.

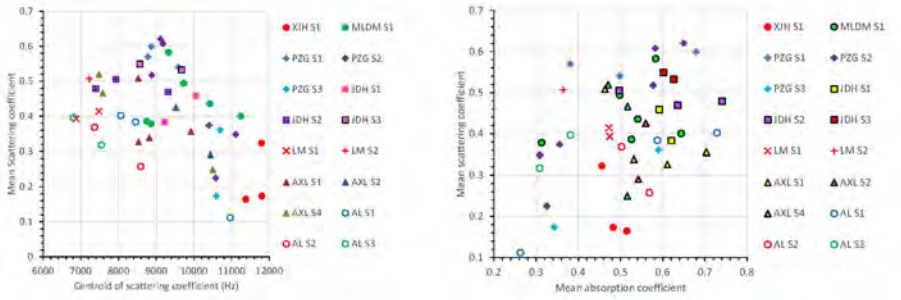


Figure 6. Acoustic results for micro-acoustic patterns series, with centroid of scattering (left) and mean absorption coefficient (right).

4. Discussion: Results, Glitches and Defaults

In scattering disc design, a concept of randomness can support aesthetic variations over a field of modules that follow the same code or DNA and with variable surface characteristics. Firstly, controlled randomness could be applied as a strategic, intuitive and exploratory design tool. The controlled concept of randomness was inscribed on multiple levels. Each particular design embedded randomness through the processing code, by applying scripts that, in themselves, are inherently random. Across all scripts, generic deformations were introduced by manipulation attractor points, boundaries, and particular zones of densities. Furthermore, by increasing

number of points, the pattern accuracy could be increased. Randomness could be generated by variations of multiple criteria sets such as robot motion path relative to points, rotation technique, angle, or line height. Randomness could also be introduced shape of tool, as non-finite expressions of a shape range due to the physical manipulation of a wire profile through bending. These parameters then included the shape of the wire, depth (in z plane) of wire, angle at which the cut is produced, variations in the z plane. By executing different machine code sets by interruption, recursion, or shift to another surface, different locations and parts of patterns could be generated.

Secondly, randomness in the robotic tooling process could be referred to as material and machine constraints, failures, and errors from initial assumptions as part of the manufacturing process. Multiple pathways across the surface resulted in overcuts (taking of too much material, thus producing a shallow sample: JDH_T01). A combination of multiple overlapping points, slow machining and a high density of cuts in area led to overburn in areas where hot wire continued cutting (JDH_T01). Discrepancies between robotic tooling simulation and actual machine path in material occured. With an undercut distributed in several directions by an end-effector with a closed profile (as opposed to open V-shapes), complex shaped tools (U) led to unresolved undercuts, where waste fragments could not be removed, thus resulting in a less effective panel in terms of scattering and absorption (AL_T01). Here, directional cuts had to be devised in order to eliminate hindrance form material waste, so that loose parts could be dislodged with ease. Finally, while controlled robotic tooling across a sample series produced subtle variations, the overall differences and densities in the surface valleys actually produced optically differing, but acoustically alike micro-patterns (AXL, MLDM, PZG). Effective sound scattering qualities were closely followed across sound variations. This suggests that regardless of which section of script is manufactured, results will have similar trends when equal valley depth and material subtraction is achieved. As a result, a percentage of pattern densities relative to the surface area was determined a significant factor for further investigation.

5. Conclusion and Future Research

This paper has discussed empirical research into the acoustic performance of randomized patterns based on degrees of variations in code, supported by quasi-predictable variations in a computational process, and by select variations to robotic fabrication. Different series were produced that extend the spectrum for manufacturing diversity in micro-geometries, and tendencies for acoustic behavior in scattering and absorption could be demonstrated through scale model 1: 10 prototypes in a scale model reverberant box. Through the empirical study of pattern generations within multiple criteria (parametric modeling to scale model production to physical simulation), the acoustic reflective properties of surface patterns were tested for scattering performance, and these tendencies will need to be further investigated. While the aim of this first series had been to find an empirical relationship between a physical parameter and acoustic result, further approaches will need to include a differentiation of ratio between surface area, depth of cut and pattern frequency; through measurement and integration of the 1) of surface

area of the disc, which can be expressed as a ratio to the flat disc prior to cutting; the 2) root-mean square (rms) depth of the surface (subtracting mean depth); or the 3) circular FFT power spectrum around the surface (at various radii) as the most detailed approach. The research has thus resulted in a larger spectrum of scattering-effective acoustic micro-patterns in a robotic subtractive process, by which new design strategies for acoustic performance in the built environment can be applied. Acknowledgements: This research is supported by a 2015 SEED grant from The Sydney School of Architecture, Design and Planning, The University of Sydney, and has been developed in CodeToProduction 2016, with support of the Audio&Acoustics Lab, and with support of the DMaF Robotics team, Rod Watt and Lynn Masuda.

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ROBOTIC SIMULATION OF TEXTILE AS CONCRETE REINFORCEMENT AND FORMWORK

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Abstract. New possibilities of concrete constructions in architecture, the traditional formwork can be gradually replaced by the use of flexible textile. At the same time textile reinforcement combined with fabric formwork, introduces an innovative integrated solution in the fabrication of concrete. Based on a simple understanding of the textile weaving and knitting techniques, this project concentrates on the architectural production and the structural optimization of the textile as both concrete reinforcement and formwork. Furthermore, we present a robotic simulation of the process that develops using a series of computational experiments to research the sequence of weaving and/or knitting. Through the computational process and the design simulations, the research is firmly rooted in analog and digital exploration of material and its implementation in architecture, with particular emphasis on the convergence of robotics and computation. Note that the paper deals mainly with the software and weaving simulation as part of a larger research project, without dealing with the production of physical artefacts.

Keywords. Robotic weaving; textile-reinforcement; parametric design; lightweight structure; textile-reinforced concrete.

1. Introduction

Technology for robotic fabrication has developed since the 1980s. Simultaneously, an extensive scope of intrinsically architectural themes of fabrication and technique is developing onto the current agenda (Fereos & Tsiliakos 2014). At the same time recent advances in textile fabrication showed the advantage of using textile-weaving techniques to create structural shells. Due to the high cost and

the complexity of construction, the applications of shell like structures have been limited. Therefore, it is necessary to develop robotic fabrication to achieve geometric freedom and decrease the budget. Within 3D modeling software Rhino and Graphical algorithm editor software Grasshopper, a parametric system of simulating weaving of textile was introduced, and an investigation of several approaches to address the stresses on the shells and the external forces by using Grasshopper's plugin Millipede based on Finite Element Methods (FEM). Finally the robotic fabrication of the weaving was simulated related to previous experiments.

Notice that, the structural performance and durability of concrete systems may be improved by introducing high-strength textiles with different permeability, interlacement structure and load-bearing capability. And besides, the use of textile may reduce the use of timber in vertical supporting formwork and, therefore, minimize reliance on timber resources (Mcquaid & Beesley 2015). Hence, the work presented is novel in the following regards: the production of lightweight, continuous, textile reinforcement and in tandem formwork for concrete shells will reduce waste and increase the economy of concrete structures by creating smaller lighter building cross-sections.

2. Background

One of the streams of robotic fabrication in architecture has been the novel combination of computational techniques into integrated design, test, adapt and fabricate systems. Some studies have ventured into adaptive stacking of architectural elements, in an exploratory open framework (Narahara 2013), or attempted to create an integrated framework of computationally driven, robotic actuation and fiber-stiffening process of shell-like inflatable structures (Poinet et al. 2016), after a critique of post-rationalized geometry input into fabrication methods, where the focus is on saving material, being economical due to constraints. Again shell geometries seem to be a good target selected by the CAAD community for robotic fabrication, for example integrating behavioral design and adaptive robotic fabrication of a compression shell, with the aid of a pneumatic formwork (Doerstelmann et al, 2015). Double curvature surfaces are also the subject of integrated approaches in creating special machines to form them, for example by custom presses of a material, with the press actuated by robot (Fereos & Tsiliakos 2014). Integrated processes can be shown also to be efficient when developed into a dynamic direct framework, such as in the study of (Braumann & Brell-Cokcan 2015) who developed direct, dynamic, bi-directional, parametric controls of robots instead of the packaging and sending of tool paths to robots at the end of the parametric design process. Within this field, this research integrates design, simulation and physical material constraints.

3. Research and Analysis: Importance of Fabric Structure

With the advancement of new techniques for material inventions and constructions, the possibility for freeform geometries make it timely to review the design and fabrication techniques in not only architectural design but also structural engineering. This computational revolution made possible a massive improvement in complex-

ity and freedom, widening the collection of architectural shape (Grasser & Brueck 2011). The form finding process based on computational algorithms is consisted of three crucial principles: modeling of desired geometry, transformation from pattern to structural elements and optimization of force distribution (Ahlquist & Menges 2011). In this project, the vital part is simulating the weaving and knitting pattern and conducting the textile parametric experiment. On the basis of the prototype analysis, the project further studied the role and significance of structural performance-based tools in structural design.

3.1. OVERVIEW OF THE EXPERIMENTS

We introduced a series of experiments to test material recognition in the computational design process, and create the overall textile structure considering form, loads and material properties integrated. The parametric generative form finding aims to explore the material nature and entire of an architecture arrangement, a valuable process in comprehending the connection between geometry, material and force. Consequently, we started creating weaving patterns and interlocking structures to test how they may be utilized in both concrete reinforcement and formwork. After applying the weaving pattern to the different geometries such as a surface, a column, a falling mesh and a vault, we used Grasshopper's plugin Kangaroo to conduct a series of physics-based experiments to understand the relationship between the geometry and the exterior forces. Through applying and simulating different forces on the surface, the reinforcement geometry can be changed in relation to the stress analysis, and therefore, optimized. Moreover, considering the use of textiles as structural formwork, we used an advanced plugin Rhino Vault based on Thrust Network Analysis to modify the horizontal and vertical force diagram in real-time. The final step was finding stress and strain lines in the loaded surface and optimize the shape of loaded surfaces by using another Grasshopper's plugin Millipede based on Finite Element Method (FEM) to define the material, loads, supports, deformation axis and vector where is load is being applied. The robotic fabrication simulation following as the last experiment in line simulates the tool path of the robot and optimizes the final artifact production. Note that the process we present at this paper deals mainly with the software and weaving simulation as part of a larger research project, without dealing with the production of physical artefacts.

3.2. WEAVING AND KNITTING SIMULATION

Our logic to create interlocking structure using now is based on weaving, knitting, braiding, and sewing. Each of this process with different methods and techniques to create knots and each of these methods can be made available for industrial fabrication by using specific machines such as, looms to weave, knitting needle to knit, braiding machine for braiding. Borrowing and learning these methods that already have been put into manufacturing can combine the simulation and fabrication tool repository combined to create new prototypes.

The experiment of the simulation work focuses on the application of tools, exploration of the technique, and subsequent development of an informed design intuition for generating the weaving pattern in a fabric. Specifically, we will ex-

amine how the Grasshopper with physics engine plugin Kangaroo explored the design process for form finding, geometric articulation and structural optimization. Figure 1 shows the procedure is creating a weaving surface like fabric. The first step is to set one surface on Rhino and then divide it to create perpendicular grids. For each intersection points on grid, the normal is found. Therefore, the interpolate curve through the points can be weaved.

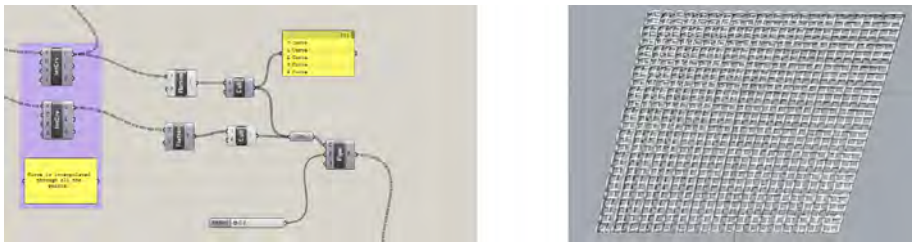


Figure 1. Creating weaving surface like fabric.

The introduction of Kangaroo as a physics-based simulation engine has further extended the software program to include a dynamic physics algorithm, thus allowing designers to visualize the physical forces interacted with their designs (Huang & Lewis 2014). The following stem aimed to see how the weaving changes under a load of gravity. So in a way, the stress and strain and elastic deformation of the weaving itself can be seen. This may actually help, as many fabrics, such as polymers or carbon and glass fibers, present a small region of elastic deformation (Calister 2007). When setting surface on grasshopper and dividing to generate points, which are going to be used to produce weaving. The normal of points is going to be used in order to control the amplitude of weaving. From the amplitude points generated, curves are interpolated and then further piped and baked (figure 2).

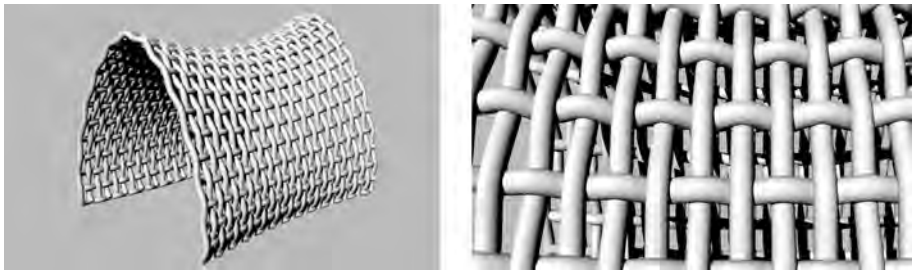


Figure 2. Design vault and applying weaving definition.

3.3. TEXTILE PARAMETRIC EXPERIMENT

In order to create a fabric as a structural reinforcement surface, we considered the analysis of primary forces: tension, compression, bending, shear and torsion. The designers cannot define the form before they understand the relationship of

geometry, material and force, thus, the route need to be studied to simulate the performance accurately at the final and full scale (Grasser & Brueck 2011). Therefore, we applied the Grasshopper's plugin Kangaroo to create physics-based simulation environments and see the results virtually. For example, in physical-based modeling, there is a usually used parameter 'spring', which followed the linear equation called Hooke's law of Elasticity (Neville 1996). It consists a strength factor and relates the displacement of an object from its initial length to force. Although materials do not always behave in a linear equation under force, the equation is still enough for an elastic simulation. In fact, the Kangaroo is contained large amount of information cannot produce accuracy completely; it offers a practicable guide to deal with the collaboration of material characteristics and primary forces (Ahlquist & Menges 2011). Based on the interacting forces, the computational process contributed significantly to form finding.

The experiment is generating a double curved shell to explore the textile parametric. Using attractor force command on kangaroo, a sphere mesh is created on kangaroo. The mesh surface is made to be attracted to the sphere size and distance from it (figure 3). Then using weaverbird command, the mesh can be smoothed and the grids on the relaxed state shell are found and the intersections point is baked. Consequently, the knitting style is done using different numbers of wefts. The more increased value for wefts, the more knitting there will be.

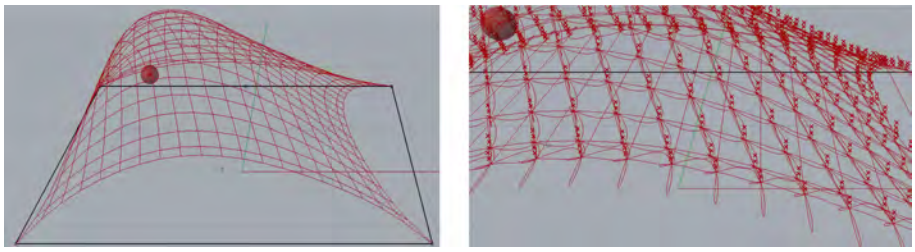


Figure 3. Grid generation and wefts control.

4. The Structural Simulation with Geometry

Not only the fabric can be used as a formwork, but also the textile can be utilized in order to act as reinforcement. The interlacing fabric formwork can minimize the penetration of air bubbles improve the surface texture quality of the concrete (Cauberg et al, 2012).

4.1. THE RELATION OF GEOMETRY AND FORCE

When considering the use of textiles as structural surfaces, where a force of tension is applied to develop stable structures, this condition is the most critical to consider. For the sake of discovering novel vaulted geometries and exploring these constrained structural systems, we used a plugin named Rhino Vault to express the stress dependencies visually between distinctive segments of the structure. By using the Thrust Network Analysis, the process of form finding can modify the stress diagram in real-time, which have an access to blur the difference between

freeform surface structures and geometry with typical tension or compression-only forms (Rippmann & Block 2013).

The first experiment is to design a simple vaulted structure by using Rhino-Vault. At the beginning, the surface on Rhino was rebuild and the control points were adjusted. For further exploring the connection between form and force, a double curved shell structure was designed using precise tension elements. The experiment showed how creates the funicular structure and how to change support settings. In this experiment, the shape of the structure and the local stress distributions were effortlessly adjusted (figure 4). Thus, the structural optimization model could be selected by defining the specific material to conduct the further physical test that simulates exterior forces such as tension, compression, and gravity and so on by Millipede.

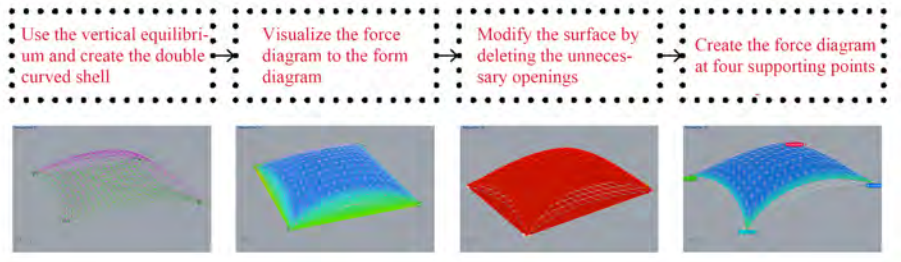


Figure 4. A double curved shell structure designed by Rhino Vault.

4.2. METHOD OF STRESS ANALYSIS - MILLIPEDE

The interlock logic of weaving gives us a way to organize individual fibrous material into an integrate structure. Based on topology optimization tools, the Grasshopper's plugin "Millipede" developed by Michalats used the Finite Element Method became an efficient structure optimization tool for linear elastic systems. In order to obtain the stress and strain lines of the resultant surface under external and self-load forces, and apply weaving to the loaded surface, a series of experiments were conducted (figure 5). First of all, with the help of grasshopper plugins such as Paneling, Lunchbox, and Weaverbird, different types of surface were created and divided to achieve grid deformation and densification according to the vector point. Surface points were moving towards the attractor point-using vector between the points as direction and curve is interpolated through points.

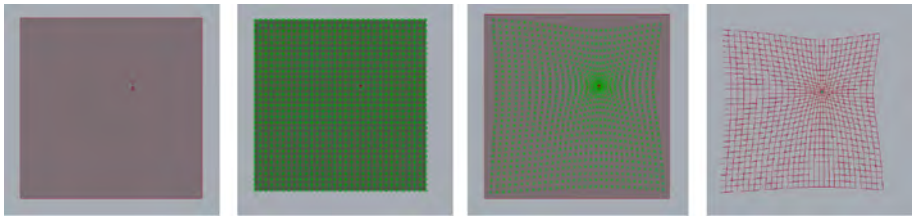


Figure 5. Grid deformation and densification on surface.

The material component in Millipede enables the user to select a stock material including concrete, steel and glass. In addition, each time the cross section type is changed, the input parameters of the component are changed so as to reflect the different geometric properties of each section. Thus, the numerical range of the results for the mesh visualization component can explicitly be set. Taking advantages of the shape and material size optimization of Millipede, we used the previous vault as the geometry to be analyzed in order to generate a network of curves. Curves are automatically intersected and discretized by the Finite Element Method (FEM) system builder (figure 6).

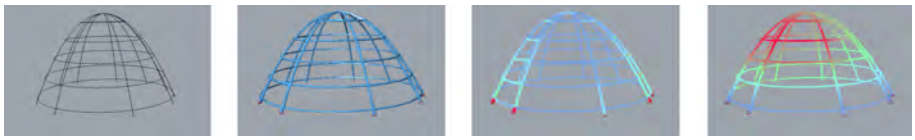


Figure 6. Basic structural analysis of vault frames.

With just 5 numbers we can explore a large family of surfaces and observe how the different shapes fair with the applied boundary conditions. Furthermore, the parameters can also be reset and connected to search for the optimization solutions. Within a fixed mesh, force is resolved individually at each fixed node. The stress can only flow and travel through the path of the open mesh material. Thus, tension force goes across the whole surface until it achieves equalization in force in a woven or knitted surface and a mesh work with a regular grid horizontal and vertical springs are used to find a balanced equilibrium of forces. An open mesh can achieve many variations in topology and still realize a tension-equilibrium form (Grasser & Brueck 2011).

5. Robotic Fabrication Simulation

With the advantage of visual programming systems for accessible robot simulation, the users can change the geometry, adjust the sequence of tool path and simulate the movement results intuitively (Braumann & Brell-Cokcan 2015). In this part, the graphical algorithm editor Grasshopper plugin named HAL was chosen as the parametric programming tool for controlling industrial robots, which supporting ABB, KUKA and Universal Robots. In addition, an ABB IRB 1600 robotic arm that payload is 10kg and the reach is 145cm was selected as an exemplary robot to simulate the sequence of tool path (Schwartz 2013). Simultaneously, we are developing fabrication methods with the research of previous various computational experiments such as interlacement woven structure on double curved shell to research the sequence of weaving.

5.1. ROBOTS AND END-EFFECTOR OVERVIEW

On the basis of Grasshopper, the HAL plugin was the vital platform to simulate and program the robots, which covering a large number of creative instructions such as multi-tasking, milling, hotwire cutting and so on. This software included a large number of libraries of different robot types such as KUKA KR10, KR120,

KR 1000, Universal Robots UR 5, UR 10, ABB IRB 120, IRB1400 and so on. Begin with creating the robot, we chose the flexible ABB-IRB 1600 robot that can be mounted on the wall and the floor. We selected the Robot Creator command to define the working range, the rotation value, the payload and the maximum speed. Besides, it is necessary to set the plane of base, six axis, rotation points and rotation center. A six-axis robot has different working range because each axis has its own rotation value in order to define the location of the end-effector such as milling spindles, gripper and weaving equipment. In this project, we create the customized weaving tool and transferred the mesh information to the robots (figure 8). For designing the specific end-effector, the first step is to create the 3D model in Rhino and convert the surface to mesh in Grasshopper. Besides, defining the center point of the tool and creating fixed plane through the original point of the tool.

5.2. TOOL PATH FOR SIMULATING THE MOVEMENT OF ROBOTIC ARMS

Like CNC machines, the subsequent task is to create tool paths that translate the data to control a robot. The plugin HAL connected the geometric model, the generation of tool path and the simulation simultaneously. We started from simulating a simple control point curve in the robot-working environment. The vital step is to confirm the start position and the end position of the movement through dividing the curve into several segments. Then the sequence of the movement can be defined by generating the position of each segment and we put the all of the positions as targets to the Tool path Creator command. Finally, all the data can be transferred to Inverse Kinematics Solver to compute the rotations of the robot joints and generate a log of movements in order to reach the target. Then we simulated the movement of robotic arms to build a woven surface and a vault. Through controlling the slider from the start point to end point, the movement of robotic arms can be simulated visually (figure 7). Notice that, when the target is out of the range of the working reach of the robotics arm, the program will produce an error log and the theoretical robot will turn to the red, thus, it is necessary to to check the working range carefully while simulating.

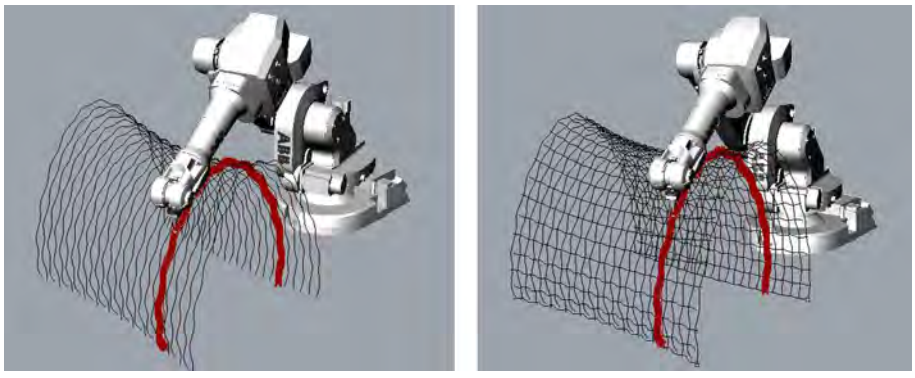


Figure 7. The sequence of weaving the vault structure though robotic simulation.

5.3. CHALLENGES OF WEAVING PATTERN FOR ROBOTIC FABRICATION

For textile-based architecture, it is really necessary to consider the reachability, the order of path execution and the possibility of interweaving. Moreover, if the fixed robotic arms are to be employed in the construction site, the designers need take the material systems into consideration to cater for problems and opportunities on the loading capacity. The maximum of reaching area for a stationary robotic ABB IRB 8700 is 3.5m*4.2m and its payload is 500kg-800kg, which it cannot reach to higher vertical distance and may need a platform to support.

6. Conclusion and Further Work

Consequently, the project addressed the simulation of textile as concrete reinforcement and formwork for designing the geometry of a knitted or weaved formwork within given design constraints of dimensions, material, and structural loading. The 3D modeling and structural analysis software indicated in this research can be used to design optimized textile reinforcements to used in both textile-reinforced concrete and formwork, meanwhile, we also envision the future robotic production of such constructions will further reduce costs and increase the quality by taping into the numerical control precision of robotic fabrication. At the present paper the focus is in the stress and form analysis and simulation rather than in the actual fabrication itself. The procedure of combining simulation, fabrication and material science into a generative and parametric methodology may be regarded as a more efficient workflow model. For the future research, we will concentrate on the process of using robots to produce the desired formwork in the actual fabrication and develop a validation framework for the evaluation of the weaving and knitting techniques.

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ROBOTIC VARIABLE FABRIC FORMWORK

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Abstract. Casting is one of the most widely used construction techniques. Complex geometries produced via computational design processes are not easily achievable through traditional rigid formwork and are subject to increase material waste. More suitable casting techniques are required to efficiently represent digital design output. This paper presents a variable fabric formwork developed to work in conjunction with a 6-axis robotic arm for casting doubly curved panels based on hyperbolic paraboloid geometry. The variable formwork is designed to be extendable in length and width so it is able to produce a wide range of outcome within a single formwork. The interface established in the workflow allows the physical formwork and digital design to influence each other. This variable fabric formwork reduces construction waste and is a more sustainable method of casting complex geometries.

Keywords. Digital fabrication; Robotic production; fabric casting.

1. Introduction

Casting is one of the most widely used construction techniques (Lloret et al. 2013) in architecture. With emerging complex geometry in computational designs, traditional casting methods using rigid formwork is limited in responding to the demand of customisable geometry. Recent research in casting using digital fabrication mainly utilises CNC milling as either sacrificial formwork (Lavery 2013) or in-situ mould (Sousa et al. 2016). A number of flexible mould designs for precast concrete have been explored using robotic slip forming techniques (Lloret et al. 2013) and multi-point systems (Adapa 2016). Traditional rigid formwork can be replaced with flexible fabric; such techniques were explored by various researchers (Pedreschi & Chandler 2007; Thomas 2015; Kallegias & Erdine 2015) as well as in commercial applications (Fab-form 2016). The appeal of the system is in its fluid aesthetic quality and the potential to re-use formwork, thereby reducing

waste in the mould design. However, there is limited research in the exploration of fabric casting with robotic arms to produce varied geometric panels using a single mould design.

This paper discusses the design and fabrication of a variable fabric formwork that incorporated the use of a robotic arm. The project, titled HYPAR, is the result of a 12-week research based design studio at the University of Melbourne lead by the third and fourth authors. The studio encourages a bottom up material approach to design, where the team investigated fabrication techniques for the design of a pavilion structure. The team explored a variable casting mould system and the potential of using non-planar quadrilateral panelised system based on the geometric principle of hyperbolic paraboloid. The outcome was a series of cast panels (figure 1) using moulding plaster; plaster was used instead of concrete for ease of casting and reduced weight in the fabrication process. This naturally made the panels more fragile and less robust compared to a concrete cast. In this paper, the design team focuses on the fabrication workflow, material effects and geometric outcome of the test panels.

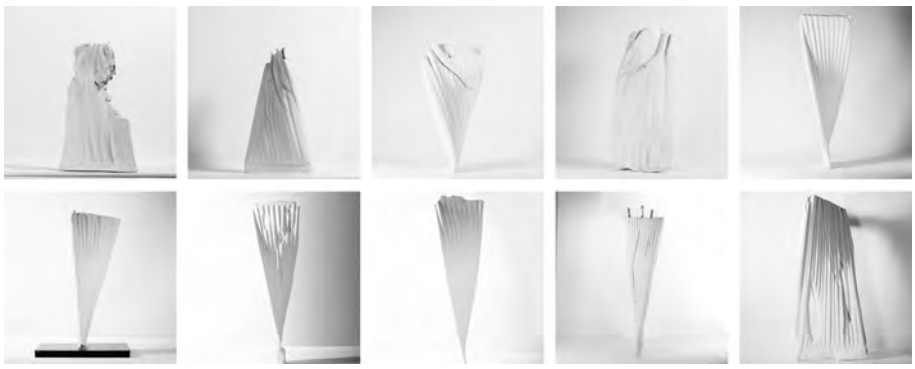


Figure 1. Plaster cast hyperbolic paraboloid panels.

2. Background

Soft and transformable formwork in casting has been explored by numerous practitioners. Pneumatically supported tubular formwork systems were used as early as 1938 to construct water pipe lines (Sobek 1986). In the 1960s, Bini established a method of casting concrete shells with inflated membranes (Roessler & Bini 1986). Unlike conventional rigid formworks, soft formworks have the capacity to cast more complex geometries; namely doubly curved surfaces. The results are typically of thinner shells which are structurally more efficient.

Most soft and transformable formwork utilises fabric as the key material. Significant developments in fabric formwork were made in the late 18th and the 19th century as a result of the Industrial Revolution (Veenendaal 2011). While traditionally seen as utilitarian application for its simplicity and cost effectiveness, it was not until the 1950's that fabric formwork was used and explored in architectural projects by Miguel Fisac and later by Mark West (CAST 2016) and Kenzo

Unno. Veenendaal (2011) outlined the limitation of research in this field and identified the key challenges, for example the double curvature geometry is implicit to the fabric formwork and this tends to limit its application in traditional design.

2.1. USE OF ROBOTICS IN CASTING TECHNIQUES

Recent research projects in casting explored the use of industrial robotic arms to manipulate variable formworks to explore novel techniques and material expressions. While the research in this field is limited, there are two key projects that are relevant to our discussion. First, the Robotic Slipforming project conducted at ETH Zurich, which used a robotic arm to manipulate a cylindrical formwork, which was rotated and extended in height to form "double curved" columns (Lloret et al. 2013). The second project is Fabric Form developed at UCLA which utilised two robotic arms to stretch a truncated fabric formwork to a scripted geometry, resulting in concrete components that could be accumulated to form a lattice structure (Culver et al. 2016). Both projects utilized the robotic arm as the primary device to produce trajectory for the formwork in order to move it from its start to rest position. Here, the choreography of the production process conditioned by the anatomy of the robotic arm delivered a set of dynamic rules which could become a driver for design (Ameijde et al. 2012). As Gramazio and Kohler (2008) pointed out, "We design a behavior".

2.2. RULED SURFACE GEOMETRY

The geometries produced by HYPAR are based on hyperbolic paraboloid, a doubly curved saddle-like ruled surface. In architectural design, this geometry has been widely used, most notably in the geometric development of Sagrada Família (Burry 2011A). Similar geometry is also deployed in the roof structure of St Mary's Cathedral, San Francisco by Nervi. Here, eight hyperbolic paraboloids are used to generate the spatial transformation from a square on plan to a cross at the apex of the roof. The assembly of the roof is made possible by utilising a straight timber plank as scaffolding to support the triangulated pre-cast concrete panels (Nervi 1965); it demonstrates the advantage of deploying ruled surface in the construction of a complex doubly curved roof.

There are three key characteristics of the hyperbolic paraboloid that is critical to the project. Firstly, for any ruled surface, a single straight line lying on that surface will pass through a given point lying on that surface (Burry 2011B).The straight line is referred to as ruling. For hyperbolic paraboloid, every point on the surface has two lines passing, making it a doubly ruled surface. This geometric property makes hyperbolic paraboloid load-resistant in two directions (Farshad 1992) but more importantly, the ruling as straight line or edge can be articulated as physical material which is useful for the fabrication of the mould.

Second, it is important to note that not all ruled surface geometries are developable. Hyperbolic paraboloids explored in HYPAR are quadric surfaces which are non-developable; as the ruling consists of non-torsal generator where the tangent plane at any point on the surface is different from other points on the surface (Portmann et al. 2007). Despite the non-developable nature of the surface, it is

possible to define this "warped ruled surface" geometry by the four corners of the quadric surface. In HYPAR, we reduced the four corners into two opposite edges as the primary parameter.

Third, the nature of the geometry allows the possibility of joining hyperbolic paraboloid panels at their edges. The characteristic of this second order geometry as Burry (2011A) pointed out can be fragmented into individual components which when combined can still form a seamless surface. The complexity comes when the surface assume a thickness as in casting a panel. The four edge faces of the panel would also be ruled warped surfaces. These three characteristics of hyperbolic paraboloid are used as the primary parameters in the design and development of HYPAR.

3. Design and Fabrication of Variable Mould

HYPAR is designed as a variable fabric mould controlled using a 6-axis robotic arm. Figure 2 illustrates the design of the latest iteration of mould. This mould is used to cast a 300mm wide x 900mm length x 50mm thick panel. The mould consists of the following parts:

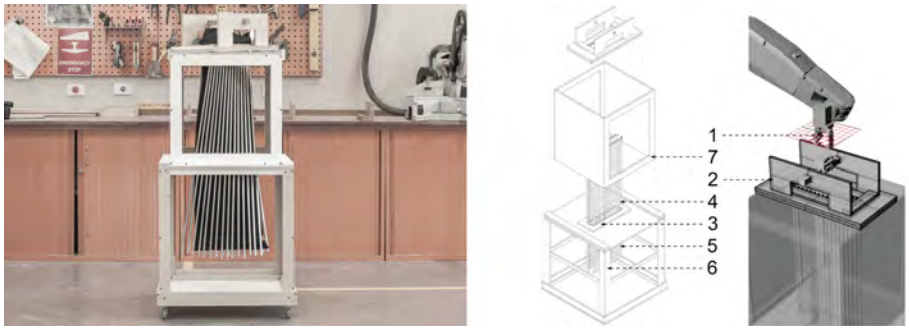


Figure 2. Variable mould and diagram showing parts.

1. Bespoke end effector. The end effector attached to the robotic arm is a gripper with a pair of 3D printed ABS plastic teeth. A pair of negative teeth is screwed onto the top clamp (2). The end effector is driven by compressed air so the robotic arm could hold the mould in position and release the formwork after the curing process.
2. Top clamp. A CNC milled MDF panel with a pair of bespoke clamps where the fabric formwork and aluminium tubes are fixed to a horizontal plate. The width of the panel is pre-set but the mould can be adapted to increase or decrease its width.
3. Bottom clamp. A CNC milled MDF panel with a slot acting as a guide for the ruling aluminium tubes. The bottom width of the panel has potential to vary in width as per the top clamp.
4. Ruling. Consisting of 30 pieces of 1 meter long hollow aluminium tubes at 20mm centers. The tubes are pin jointed at the top clamp (2) but are not constrained at the bottom, which allows certain amount of movement and rotation. This allows for variation in length (L) to the panel, in this case the length constraint is 388mm < L < 900mm.

5. Fabric formwork. The fabric used is a mixture of 95% polyester and 5% lycra, stitched with a sewing machine into a rectangular shaped pocket. It is placed in between the ruling and is only clamped from the top with an opening to allow the pouring of plaster.
6. Carcass. The carcass is CNC milled MDF and softwood timber framed supporting the bottom clamp. It does not support the weight of the cast which is primarily held up by the robotic arm.
7. Temporary frame. The frame is removed after the robotic arm engages with the mould via the end effector (1).

For individual casts, the bottom edge of the fabric formwork (5) is fixed at the same place at the bottom clamp (3), but the height, rotation and tilting of the top clamp (2) can vary for each cast, and thus generating variable formwork.

In the development of this variable fabric formwork, five iterations of the mould were made and improved over the 12 weeks' period. The first mould was designed as a manual input device to attain the basic principle of hyperbolic paraboloid cast with the aid of elastic cables along the fabric to retain the ruling of the surface. Once a successful cast was made manually, the robotic interface was developed to pair the formwork with the 6-axis robotic arm. The research utilised an ABB IRB 1200-5/0.9 with a 901mm reach and 5kg payload.

A significant improvement to the system happened when the design team abandoned the elastic ruling in favour of a rigid tube system constrained in one direction. This minimised uncontrollable bulging of the fabric under hydrostatic pressure of the plaster.

Further improvements in the final iteration of the mould (figure 2) were made to increase the height and thickness of the cast, with this came the need for stronger ruling component along the side of the fabric to hold the cast. The design team also integrated pipes in the final cast and developed design opportunities for apertures; this is discussed in 4.2.

The main differences of HYPAR with the projects listed in section 2.2 are:

1. HYPAR is designed to produce non planar quadrilateral surface. The double curved nature of the fabric formwork highlighted in 2.1 is useful in the design and development of the surface.
2. Unlike Fabric Form by Culver et al. (2016), the fabric formwork utilised the "ruling" of the hyperbolic paraboloid surface as a principal to extend the length of the panel. In practice, the panel can vary in width and length.
3. If the length remains constant or within strech limits of the fabric, the same fabric formwork can be reused to produce variable geometries.

3.1. FABRICATION WORKFLOW

The design team stimulated the making procedure on numerous occasions before using the robotic arm to engage with the mould. Figure 3 demonstrates the making procedure of the panels. Ten separate casts (figure 1) were made in order for the design team to acquire and develop the skill of casting; each getting progressively larger in size from 300mm to 900mm tall. The iterative procedure allows the

system to be refined, for example, in how to control leaks and poor workmanship issues in the mould.



Figure 3. Fabrication workflow of HYPER.

As discussed in 2.3, this second order geometry has a unique characteristic that enabled a doubly curved surface, for example a shell structure, to be panalised and combined together to form seamless curvature. The design team tested the hyperbolic paraboloid geometry onto a shell structure as a design response to the studio brief (figure 6-A). The geometry of various hyperbolic paraboloid panels as the outcome of the design were taken as the input to the digital workflow. A visual script was written in Grasshopper to generate a robot target frame for any hyperbolic paraboloid panels. As illustrated in figure 4-A, the panel is oriented to align with the bottom clamp (figure 2-3) of the mould in Rhino 3D. A plane is defined at the centre of each panel's top edge and is offset to the top clamp (figure 2-2) position. It is referenced as one of the target frames for the robotic arm where the fabric mould is formed into the resulting hyperbolic paraboloid geometry. Other necessary target frames (figure 4-B) indicating the starting position of the robotic arm, its gripper closing position and temporary frame removing position are part of the movement information which translated into the trajectory of the arm for each corresponding form.

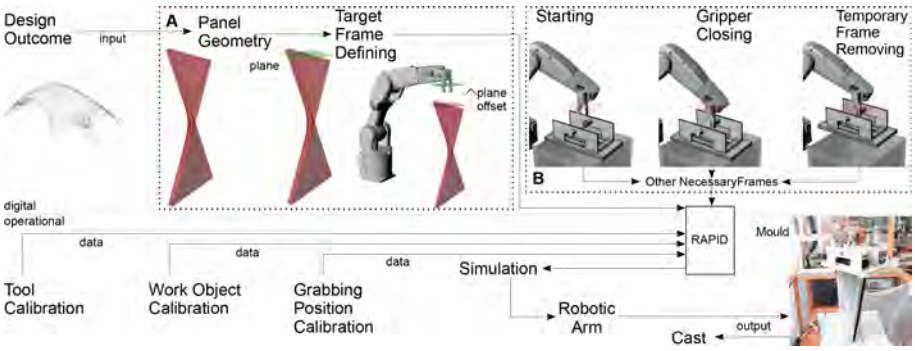


Figure 4. Robotic workflow of HYPER.

3.2. INTERACTIONS OF ROBOTIC ARM AND MOULD

The interface between the mould and the arm became a critical aspect in the fabrication process. While digital stimulation of the robotic arm was already undertaken

in RobotStudio 6.03.01, this only allowed the team to understand the trajectory of the arm without material constraints. There were other factors missing from this stimulation, for example, what was the reach limit in relationship with the ruling tubes? What was the maximum angle of rotation before the ruling starts to collide? Data collected from these questions allowed the team to feedback the information into the form generating Grasshopper script.

In order for the design team to develop and understand the limits of the mould with the robotic arm, the team tested and explored the limitations of the mould without any cast as physical simulation. Placed within the range of the robotic arm, the mould was jogged to its limitations along X, Y, and Z axis. A so called capability boundary can be recorded in this simulation process (figure 5) and it was used to mark out the geometry range in the robotic coding. Here, the interaction between the robotic arm and the mould constructed limits in the design. The mould is used to "teach" the robotic arm to understand the limits of the system; the information is written back into the form finding script to optimise the size of the panel subdivision.

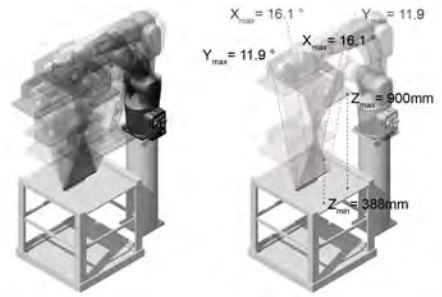


Figure 5. Left, Robotic arm and mould interaction. Right, Capability boundary of the system.

4. Future Inquiry and Potential

Current research has identified limitations of the system. For example, the mould design is hindered by the pin joint of the ruling tube which limits the rotation of the robotic arm; this could be improved using rod end ball bearings. The robotic arm, however flexible and accurate, had a weight limit which was reached upon casting a 900mm tall cast; efforts to cast larger and wider panels would require robotic arms with larger payloads. Despite the limitation of research tools, the fabrication method explored in this paper provides a starting point towards a more sustainable way of casting multiple unique doubly curved panels.

The key challenge of the system was confronted when the panel assumed a thickness and individual panels needed to be butt jointed together edge to edge. In the current mould design, the edge is treated with aluminium tube ruling. However, because of the 50mm pre-set thickness of the panel, the ruling aluminium tube did not produce a sufficiently tight tolerance for the panel to be butt together as a male and female slot. This will continue to be investigated in future research.

4.1. DESIGN IMPLICATION AND POTENTIAL

As discussed in section 3.3 and 3.5, the team tested the geometrical possibility of HYPAR in a shell structure design. The limits of the system was identified through the interaction of the robotic arm and the mould provided the parameter for the architectural proposal (figure 6). Through the material study, two potentials of the design are worth noting. The first is the potential of the hyperbolic paraboloid surface to act as acoustic diffuser where the twist of the individual surface can be parametrically adjusted.

The second potential emerges from the fabrication process. While the elastic ruling is replaced with aluminium tube system which minimised the bulging of the fabric under hydrostatic pressure of plaster, the fabric continued to bulge in between the aluminium tubes, this was seen as an interesting visual effect that the design team wanted to encourage. It allowed the design team to consider embedding pipes within the cast for evaporative cooling purposes. Pipe embedded building envelope has been developed recently to reduce heat transfer through facades which have the capacity to utilize passive cooling instead of mechanical cooling (Shen & Li 2016). Other researchers have been exploring the potential of porous ceramic pipes to absorb water and act as passive cooling devices; the potential of the research is in the capacity to combat urban heat island effect (Chen et al. 2015). HYPAR explores the potential of these evaporative cooling techniques through imbedding water pipes that could release water from within the cast allowing it to saturate the outer surface, creating a cooling effect in conjunction with air movement. Initial analysis of the cast panel suggests that the aperture in the panel has the capacity to create disturbance to increase air to surface contact, thereby assisting evaporative cooling through the process (figure 6).

5. Conclusion

HYPAR suggests a novel fabrication technique which integrates a robotic arm within its fabrication protocol to produce hyperbolic paraboloid cast panels. While the current design has limitations, the research identifies future area of research for fabric casting using robotic arms. The design procedure of the mould highlighted the need for interaction between the robotic arm and the mould in order to set up a continuous feedback procedure to improve the various iterations of the mould. It set up the digital workflow that has implications on the form generating process; integrating the logic and characteristic of hyperbolic paraboloid geometry and translates this into material articulation and behaviour of the robotic arm, resulting in the transformation of the geometry. This fabrication method proves to reduce material waste and manual labour in the construction of complex doubly curved panels. The mould design is a step towards a more sustainable means of construction in the wake of parametric and computational design application to construction. The responsibility, however still lies with us as designers and architects to construct new ways of reducing impact to our built environment, not just through design performance but also closely integrated into the construction process.

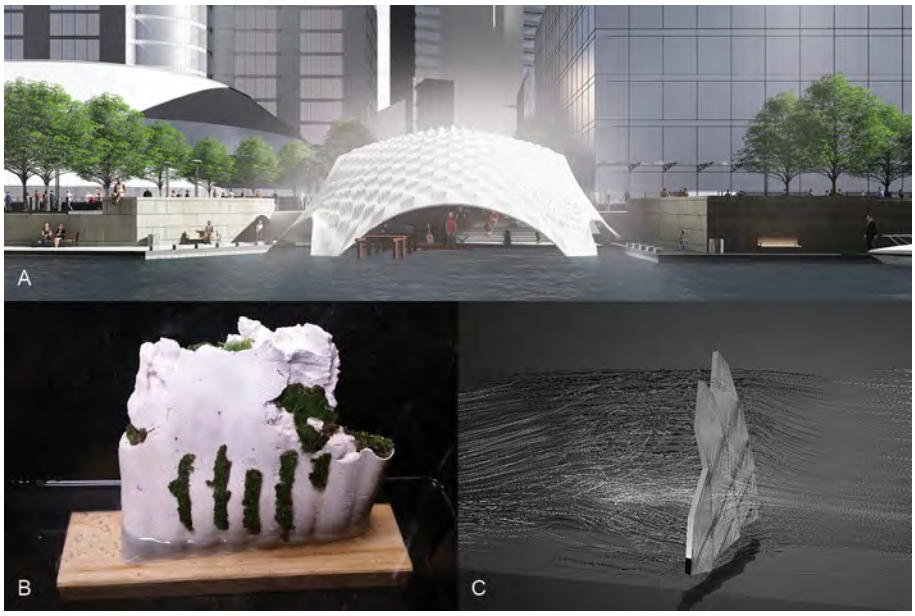


Figure 6. A, The architectural proposal. B, Moss growth demonstrating absorption of water by the cast. C, Wind study of apertures.

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FABRICATING WITHOUT CAD MODELS

Experiments with G-code and KUKA KRL

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Abstract. This research focuses on the transformation from design to fabrication without CAD models. In contrast to the conventional "design - modeling - fabrication" workflow, which involves multiple software, we experimented with a method of programming the bespoke fabrication process, and consequently defining the artifact. Algebraic models are employed to specify the materialization process carried out by various CNC machines. We used the programming language Java to create machine instructions for 3D printers, milling machines, and robots. In this method, design and production are not two separated processes; rather we regarded them as two aspects of one whole activity. Proficiency in machines and materials could contribute to design innovation.

Keywords. Digital fabrication; computational design; java; G-code; Kuka.

1. Introduction

How are designs usually sent to CNC machines? A solution is the "3D model - slicing - tool path" pipeline. However, herein, we explore a more straightforward approach: directly programming the machine codes so design and production become two aspects of one activity. Our motivation of mastering machine codes is to innovate designs through a highly individualized fabrication process, rather than in a standardized procedure of using machines. The "3D model - slicing - tool path" pipeline reflects a mindset of "produce-as-it-is" among architects. Many people would be satisfied if the final product is close enough to the CAD model they built. Following the aggressive footsteps of digital fabrication over the last decade (Gramazio et al. 2014), some designers began to migrate to another mindset: "design by fabrication." Pioneers in digital fabrication have shown that the design process driven by logics of material and fabrication is promising (Hua 2014). With this insight, this paper discusses how mastering machine codes can contribute to innovative designs.

Using and developing standard CAD models has deeply influenced how architects think about design and computing. CAD models are usually inadequate for fabrication or construction without the aid of additional software and expertise. Many manufacturers of CNC machines (for example, ABB's RobotStudio) strive to provide user-friendly software for specifying the fabrication process. There is also software such as NX (Siemens), CATIA, and Rhino/RhinoCAM that promise to integrate design (CAD) and manufacturing (CAM). Despite the abundance of commercial software, architects have to make their own software and even build their own bespoke machines (for example, Budig et al. 2014) when the desirable machines and processes are so individualized that standard technology no longer suffices. Subsequently, design and fabrication are blurred at the boundaries.

In a series of projects, we designed (programmed) the machine instructions rather than filled the gaps between CAD models and CNC production. Such a shortcut is valid for both additive and subtractive manufacturing - it would not be limited to specific machines or languages. We found formal languages (in particular, algebraic models) suffice to define the machines' tool path and, consequently, the final product. A generic programming language, e.g. Java, could be employed to transform the algebraic representation into discreet data and finally into machine instructions. The results suggest that, if one negotiates the design and fabrication from the outset, "fabrication without 3D models" is a promising method.

2. Machine Codes vs. CAD Models

"A model is a work of fiction." Cartwright (1983)

The CAD models' advantages in design and production have been widely recognized. First, parametric modeling software (for example, Sketchup and Rhinoceros) provide intuitive and versatile interface for 3D modeling. Second, using CAD models means access to the enormous amount of technologies and tools built on CAD models. Third, as 3D representational models like mesh models are well-established industrial standards, it is great to share the same model across various tasks such as scanning, modeling, rendering, analysis, and production.

Despite the central role of the CAD models in design and fabrication, we are concerned with a number of scenarios in which directly editing machine instructions is simpler and/or better than using a conventional workflow involving CAD models:

1. To cut four identical squares using a laser cutter (figure 1), the standard way is drawing four separate squares in a CAD file. However, one can first cut a cross and then a rectangular boundary to produce four squares, via editing the machine instructions (e.g. G-code). The latter approach saves material and production time.
2. To cut a ring out of a plywood board using a milling machine, the conventional way is drawing two concentric circles in a CAD file. If the outer circle is cut first, the piece will move about when the inner piece is cut. Thus, it is better to cut the inner circle first. Some machines can recognize such patterns in the CAD drawing and cleverly arrange the order of cutting, while others cannot. Nevertheless, this problem is trivial if one can manipulate the machine codes.
3. Powder bed 3D printers (e.g. Selective Heat Sintering) fabricate the workpiece

by voxels. Therefore, one should control each voxel's materialization if the aim is to access the highest resolution. However, the industrial standard of input data is the STL file (waterproof mesh), which entails certain slicing software that converts the 3D model into slices and consequently creates the machines' instructions. A high-resolution 3D model may have a size of several gigabytes, which is beyond the capacity of slicing software and computer hardware. Recently, Voxeljet (www.voxeljet.de) printers began to unofficially accept bitmap formats (one black-white image for each layer). We expect the 3D printer industry to release a standard for such low-level control of the voxel-based printers in the future.

4. To cut a flat surface out a metal piece with a milling machine, one can either place the cutter orthogonal to the workpiece's surface or lay the cutter horizontal to the surface. The two approaches will result in two flat surfaces of distinct appearances. CAD models do not address these issues, which are usually left to the CAM software coupled with the CNC machine. Nevertheless, making a flat surface is indeed about design instead of a fixed routine. By working with the machine codes, one can access the finest details of machine- material interaction.
5. To produce a series of Platonic solids (tetrahedron, cube, octahedron, etc.) using a hot-wire cutter to cut polystyrene foam, the conventional way is modeling the solids in a CAD software, and then employing CAM software to generate the tool path. However, the tool path could be directly determined by the position of a family of symmetric planes whose intersections result in a Platonic solid. Here it makes sense to focus on the nature of fabrication rather than on the nature of the 3D model.



Figure 1. Cutting four squares.

To summarize, the advantages of editing machine codes over using CAD models are: First, fabrication is characterized by sequential movements of machines. CAD models contain no dimension of time, while machine codes are a sequence of commands for the machine's movements. Second, mastering machine codes allows the designer to control the details of tool-material interaction. As both designer and maker, one would think about the "design-fabrication" pair from the outset. CAD models have their own merits: First, the visualization provided by CAD models exceedingly facilitates design and communication. Second, the industry has been optimized based on CAD models, thus it is not likely that CAD modeling will be replaced by editing machines codes in the near future. One may reconcile the two methods by embedding the functionality of machine codes editing into standard CAD/CAM or BIM software.

To be proficient in machines and automation, many designers have begun changing the machines or developing end effectors (Budig et al. 2014). Design and production innovation are so close that the two can hardly be achieved separately. Designers seek novel links between the physical reality of machines and materials and novel design ideas.

3. From Algebra to Artifact

"Modeling in its broadest sense is the cost-effective use of something in place of something else." Rothenberg (1989)

Representing geometry with algebra can be traced back at least to René Descartes; however, one was not able to instantly transform algebra into shapes or tangible objects until there was widespread availability of digital tools. Thanks to the easy access to programming tools and CNC machines, we can swiftly receive feedback from the visual or tangible objects defined by algebra (or other formal languages) and, consequently, modify the algebraic model to proceed to better results.

There are two main steps from algebra to tangible artifact: discretization and materialization. First, we sample discreet values from the algebraic representation of the desirable design and put the values into a certain format of structured data (e.g. G-code). Second, the machine uses the data to produce the artifact. Therefore, data serves as a bridge between formal representation and the physical reality of machines and materials. It is convenient to work on the level of machine codes to integrate artifact, design and fabrication. The following projects give examples of how design and fabrication are organized by algebra instead of CAD models.

3.1. 2.5D PRINTING OF VASES

A G-code-supported 3D printer allows us to implement an explicit map from algebra to artifact. Java was employed to convert the trigonometric functions into the 3D prints. It is well known that the expression $(x = r\cos\theta, y = r\sin\theta)$ corresponds to a circle of radius r. The parameters θ, r stand for the polar coordinates, while x, y stand for the Euclidean coordinates. Associating the radius r with angle θ (i.e., making the radius vary around the circle) transforms the circle into a parametric curve. Stacking such curves on top of each other leads to a vase (figure 2).



Figure 2. Vases produced by by an FDM printer. Each layer comprises a single closed curve represented by superposition of trigonometric functions.

An FDM delta printer was employed. The elapsed time is about 1 hour per piece (printing speed: 1.5 m/min). The print head run is 120m-150m per piece.

Each vase is about 15cm high. We opted for calling these printed vases with "2.5D objects" because the topology of each layer is a single enclosed curve represented by superposition of trigonometric functions. The vase has an extremely thin surface, and the fluctuations on the face contribute to a stability of the entire structure.

The printer's G-code is constituted of commands such as: **G1** X 22.94 Y1.50 Z1.95 E9.43. Where **G1** means linear interpolation; X, Y, and Z denote the 3D Euclidean coordinates; E denotes the extrude length of the material (heated PLA plastic). The geometric data in the G-code are directly sampled from the trigonometric functions under specific parameters. We employed Java to program the algebraic formula, generate the data and output them into a text file (G-code). Eventually an SD card with the G-code file is inserted into the 3D printer to print the artifact.

There are no explicit 3D models involved in the design and fabrication of these vases, as we simply translated the trigonometric functions into the printing data. In principle, one can produce an infinite number of different prototypes by modifying the parameters of the algebraic model.

3.2. WIRE CUT OF MINIMAL SURFACES

Electric heated nichrome is an ideal tool for cutting polystyrene foam. This project employs a hot-wire cutter to create prototypes of minimal surfaces (figure 3). The CNC cutter can align the hot wire at arbitrary angles, so any ruled surfaces could be produced. The only ruled minimal surfaces are the plane and the helicoid; however, people can approximate other minimal surfaces by a family of ruled surfaces. This project focuses on periodic minimal surfaces (Andersson et al. 1988) such as Schwarz Primitive (P) surface, Diamond (D) surface, Gyroid (G) surface, etc. Scientists have discovered these structures in both organic and inorganic materials. Designers have applied them to the design of façades, furniture, and artefacts (McGee et al. 2012).

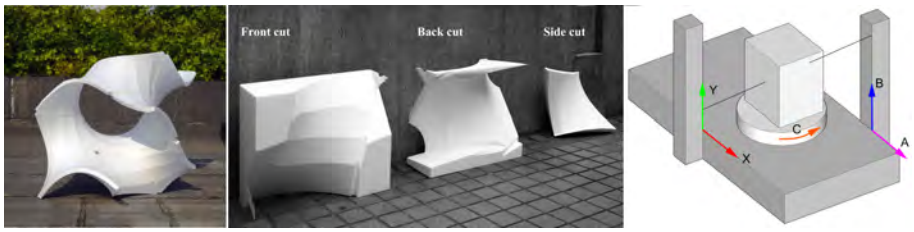


Figure 3. Wire cut of minimal surface. Left: sculpture "Gyroid" of 20 workpieces. Middle: the front-back-side cutting process for a workpiece (equivalent to two fundamental patches) . Right: 5-axis CNC hot-wire cutter.

A parametric surface has its intrinsic metric u and v. A surface is well defined if each (u, v) pair is mapped to a tuple of 3D Euclidean coordinates (x, y, z). The Weierstrass-Enneper parameterization (Andersson et al. 1988) provides such a generic map for all minimal surfaces. As the minimal surface is defined by an analytic expression, the principal direction (along which the surface has maximum local curvature) at any point on the surface could be written as an explicit formula as well.

There is a confluence of surface parameterization with the fabrication process: aligning the wire with the principal direction, and moving the wire along the asymptotic direction (orthogonal to the principle direction and to the surface normal). There are three steps to complete a workpiece (figure 3, middle): Front cut (wire aligning with the principal direction), Back cut (wire aligning with the asymptotic direction), and Side cut (wire aligning with the surface normal). The 'Gyroid' (Gandy and Klinowski 2000) sculpture was made by multiple workpieces glued together (figure 3, left). The surfaces can be extended with more pieces because they are periodic in three dimensions.

Figure 5 illustrates the geometrical configuration of a 5-axis wire cutter. Two horizontal axes (X, A) and two vertical axes (Y, B) present four independent linear movements. Adding a turntable, the fifth axis C, makes the cutting process more flexible and smooth. The G-code of the machine has the form: **G01** X1.1 Y24.1 A-67.6 B10.4 C45. The values of X, Y, A, B, and C can be directly interpolated from the Weierstrass representation of the minimal surface. We employed Java to construct this algebraic structure and then to create the corresponding G-code for cutting.

The fabrication process is completely characterized by the Weierstrass model of the minimal surface. The position and the orientation of the hot wire are derived from the algebra. There are no 3D models involved in design, nor in fabrication. Fabrication of such surfaces would become very complicated if we first build a 3D model and then try to generate a tool path from it.

3.3. ROBOTIC MILLING

The 'Panzi' project produces trays by cutting medium density fibreboard (MDF) and connecting the cut pieces by Ginkgo joints. Algebraic models are compatible with multiple machines and machine codes. In this case study, both milling machines and a robot arm were employed. The milling machine is efficient, precise, and stable; however, its cutter is always orthogonal to the board's surface. By contrast, a robot can position a cutter at various angles (Lasemi et al. 2010). We used one programming language (Java) to produce machine instructions for both machines and to guarantee consistency across different CNC systems.

Figure 4 (middle) shows a prototype of Ginkgo joints. The parametric curve across the horizontal surface prevents the two plates from moving horizontally; while the tiny gears through the depth of the plates prevent vertical movements. The curve across the horizontal surface is defined by:

$$\begin{cases} X = t + k_1 \sin(t) \\ Y = k_2 |\sin(t)| sgn\left(\cos\left(\frac{t}{2}\right)\right) \\ t \in (0, 1) \end{cases} \tag{1}$$

A spindle is mounted to the robot arm's flange so that the robot becomes a multi-axis milling machine. Notice the Ginkgo joint is not orthogonal to the fibreboard's surface (figure 4, middle). That's why a robot instead of a conventional milling machine is employed. The three layers of gears result from cutting an identical trajectory (1) with distinct heights.

Kuka Robot Language (KRL) is the programming language of Kuka robots.

We used Java, again to program the tool path and write the geometric data into a KRL format (as a .src file). In May 2016, we published an open-source library (javakuka.com) for convenient programming of Kuka KRL in Java (figure 5). There will be no third-party software involved in robotic fabrication if one links algebra with fabrication from the outset. The key benefits of javakuka project include: 1) robot kinematics formulated in linear algebra, 2) translation from geometric data to KRL format, and 3) robot visualization.



Figure 4. The 'Panzi' project. Left:trays of milled fibreboard. Middle: Ginkgo joints connecting two flat plates. Right: Robotic milling with a turntable.

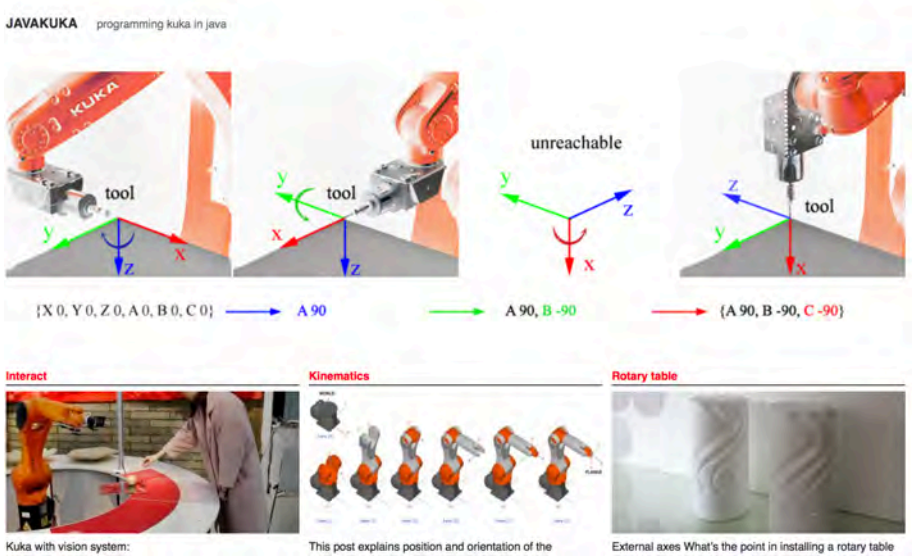


Figure 5. Open-source library: javakuka.com.

We also used a milling machine to engrave an organic pattern in the fibreboard's surface. Figure 6 is a screen shot of the computer controlling the milling

machine. The orange parts indicate the completed trajectories, while the blue parts are the trajectories to be cut. The pattern, as well as the tool path, is directly derived from an algebraic expression rather than from a 3D model. The algebraic model also specifies the uneven gaps between adjacent trajectories to balance efficiency and surface quality. This project suggests that an algebraic representation and one generic programming language are adequate in orchestrating various machines and their low-level instructions.

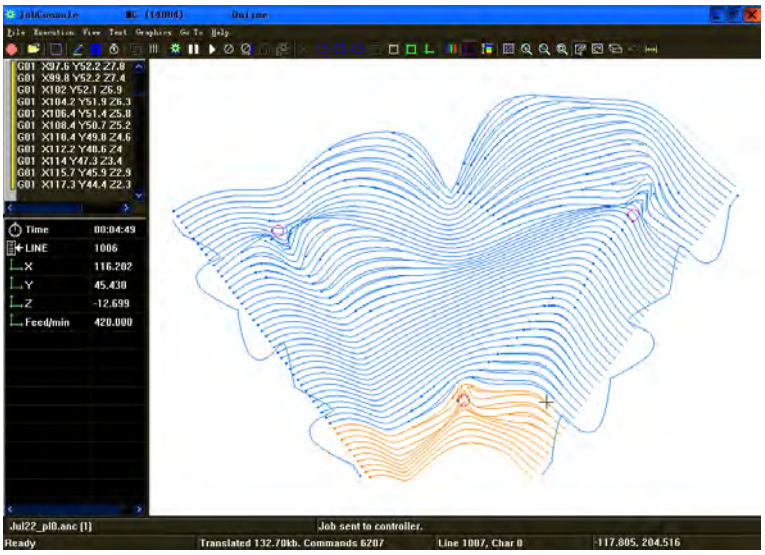


Figure 6. Tool path of milling machine.

4. Discussion

An algebraic representation defines a family of forms instead of one shape. Equipped with programming tools that can instantly transform algebra to fabrication, one is able to produce a rich variety of artifacts by using a single algebraic model. The 'one-to-many' map from algebra to artifacts stands for the most basic and powerful aspect of utilizing algebra. Programming does not only serves as a form creator but also as a generator of machine instructions (Hua 2015).

The three projects indicate that machine and design may interact in various scenarios. The 3D printing experiment demonstrates that the movement of machines (tool path) can be directly defined by an algebraic formula, which is much simpler than the conventional 'design - 3D model - tool path' workflow.

When starting with the minimal surface project, we found no off-line programming software that could translate complex geometry into machine instructions (especially with a turntable). Eventually, we found the solution of deriving cut data from the surface's algebra works smoothly. Similar to the robotic milling project, the machine instructions are created by using an open-source library rather than by employing third-party software. The true merit of programming the ma-

chine instructions is that it uncovers machine behaviors and then in turn, informs the design and the organization of fabrication. Compared to popular software such as Robotmaster, Kuka|prc which transform the geometry into robot's instructions, our approach directly manipulates the logics of fabrication. A designer will prefer the former if the design process is based on geometry; and prefer the latter if the design is based on certain formal language (such as analytic geometry) about geometry and fabrication.

In the robotic milling project, machine tools including the spindle, the turntable, and the jig mechanics are customized by the designer. More open-ended and generic fabrication devices enable us to design bespoke fabrication processes and machine-control protocols. Making machines and designing their controlling software substantially extend a designer's overall capacity to design and make.

5. Conclusions

Following the rapid integration of designers and industry, digital fabrication in architecture is on the brink of shifting from standard CNC devices to user-customized systems. Designers (especially architects) often treated fabrication as the 'next stage' of design. However, an iterative design process that continuously integrates material, machines, and design has the potential to unfold a new method of generative design (Kotnik and Weinstock 2012). Machine specifics and material behaviors not only serve as constraints to designers but as essential ingredients fostering novelty in fabrication and design. As both designer and maker, one can efficiently carry out design and fabrication without CAD models.

The conventional separations between designers, software engineers, and machine constructors had pulled designers away from the development of software and machines that now lie at the center of digital fabrication. Creating novel connections between material, machine, and design presents both a challenge and an opportunity for architects. However, to offer the client maximum value, we must now rise to the challenge and redefine our roles by integrating multiple disciplines and utilizing the most cutting-edge technologies.

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FORM-FINDING WITH ROBOTICS

Fusing Physical Simulation and Digital Fabrication

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Abstract. We present an experimental digital design and fabrication process investigating the integration of form-finding and industrial robotics. The design process is inspired by classical experiments producing minimal surfaces and tensile structures via physical simulation. The fabrication process resembles thermoforming whereby sheets of PET material are heat treated and while in a malleable state, where the material behaves like stretchable fabric, an industrial articulated robotic arm impresses a form while the sheet is air cooled and its final shape becomes stable and rigid. The three-dimensional plastic sheets are used as molds for glass-reinforced concrete casting. The key aspects of our approach include: (a) Mold-less fabrication: the design of our robotic end-effector can produce a range of free-form geometries without need for complex mold making (b) Reusable and durable artifacts: unlike traditional physical form-finding processes where the derived form is often ephemeral or fragile our process affords the detachment of a rigid artifacts which can be digitized, used as-is or employed in (c) Multi-stage fabrication: as the form-found geometry can be directly used for processes such as casting with excellent results in terms of surface finish. We present the design and development of our system and its deployment for an installation artwork.

Keywords. Form-Finding; Digital Fabrication; Architectural Robotics.

1. Introduction

Form-finding fuses geometry with aspects of its material characteristics such as tensile and compressive mechanical properties through design experiments historically involving scaled physical models, such as those by Frei Otto (Otto & Rasch

1996), Antoni Gaudi (Crippa & Gossel 2003) and Vladimir Shukhov (Greafe 1990). The setup of such experiments often predetermines topology, high-level associations of physical entities, and predefines both the loading and boundary conditions. Materials and assemblies such as thin films, strings and chains, coupled with physical forces such as gravity or surface tension become the integrated modelling and simulation primitives producing beautiful artifacts often perceived as representations of larger scale architectural and engineering systems. The limitations of working with physical models such as soap films, hanging chains, and stretched fabrics, include time-consuming preparatory work in setting up the experiments, they are often difficult to reproduce, digitize and integrate within a broader design process and they are typically sensitive to damage or direct deployment for subsequent fabrication processes.

Computational simulations and parametric modelling enable faster cycles of experimentation using form-finding principles with representations which are certainly easier to integrate within the broader design process. Nevertheless, particle-spring systems, dynamic relaxation, finite elements analysis and computational fluid dynamics are relatively less intuitive than directly working with physical models. Due to the abstraction of physical behavior, they do not necessarily produce physically correct results; or they rather span a broader realm that what is exclusively physically plausible. In addition, the materialization of complex geometries generated through simulated form-finding within parametric Computer-Aided Design software requires advanced digital fabrication technologies which rarely can faithfully reproduce the combined material and geometry logic but merely the form.

Our work investigates the domain in between physical and digital design and fabrication. The objective of the presented work is to overcome the conceptual hiatus between physical and digital form-finding, address some of the aforementioned limitations of each approach and propose a new perspective which fuses materiality with its formation process. We arrived at this discovery through design experimentation with material formation processes using industrial robotics, see figure 1. In this paper, we present the design, development, testing and deployment of our process; a case study for the design of an artwork installation created through the process; and offer insights into the notion of robotically controlled form-finding.

2. Relevant Work

Digital design and fabrication had a profound impact on the architectural design thinking and making in both academia and practice. Indicative compilation of early work in the field is presented by (Kolarevic 2003; Iwamoto 2009; Dunn 2012; Glynn & Sheil 2012). Industrial robotics have been recently popularized as a general purpose digital to the physical medium for design experimentation (Brell-Cockan & Braumann 2012; McGee & Ponce de Leon 2014; Reinhardt et al. 2016). Of particular relevance to our work are experimental design processes that do not follow the orthogonal range between additive, such as 3D printing, welding or general assembly, and subtractive manufacturing such as Computer Numerical Control machining, turning and cutting. Research work relevant to digital design and

fabrication processes inspired by form-finding includes (Kudless 2011; Dierichs et al. 2012; Clifford et al. 2014; Prado et al. 2014; Culver et al. 2016; Bechert et al. 2016). The key features of our material and processes are closer to those used in the product design and manufacturing of consumable goods based on plastics, namely thermoforming (Kruysman & Proto 2012; Weissenbock 2014), blow molding and incremental sheet forming (Black & Kohser 2003; Bruninghaus et al. 2012; Kalo & Newsum 2014; Friedman et al. 2014) but also combine aspects of processes using molding and casting. As such the presented process is rather a hybrid multistage fabrication.



Figure 1. Left-to-Right: Form-finding experiments with fabric, glass fiber and APET sheets.

3. Process Overview

The presentation of the process is organized along the following sections: (a) Material Investigations: determination of thermoplastic materials for controllable and reproducible heat treatment which can be used for casting glass fiber reinforced concrete with high quality surface finish characteristics. (b) Design Tooling: design, development and testing of the robotic end-effector including electrical and mechanical integration of heat-treatment sub-systems as well as the material positioning apparatus. (c) Parametric Modelling: motion planning, robotics simulation and software with hardware coordination. (d) Deployment and Installation: digital design and fabrication of an artwork installation comprised of three hundred parametrically varied form-found components, see figure 2.

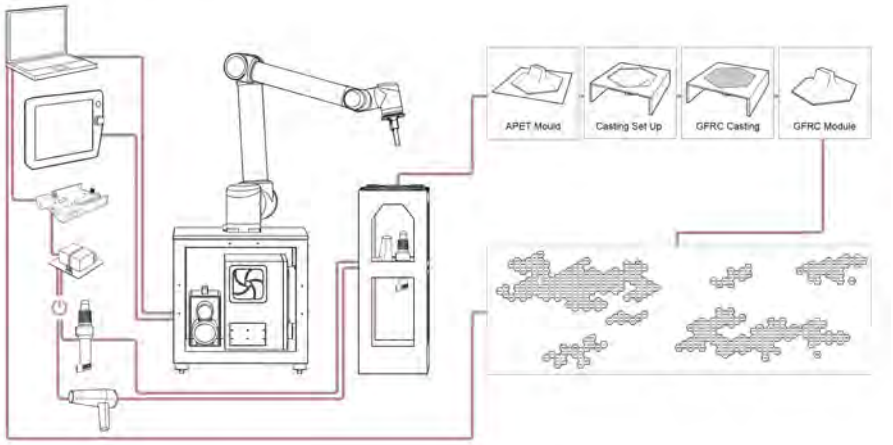


Figure 2. Process overview diagram including thermoforming, casting and installation.

4. Material Investigation

Materials used for thermally controlled forming processes of thin wall plastic products such vacuum forming, stamping, blow and injection molding (Lefteri 2007; Howes & Laughlin 2012) are commonly thermoplastic polymers including High Impact Polystyrene (HIPS), Polymethyl Methacrylate (PMMA), Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS), Polyvinyl Chloride (PVC), Polypropylene (PP), Polyethylene Terephthalate (PET) and High Density Polyethylene (HDPE). Thermoplastics exhibit a broad range of material properties such as mechanical, thermal, chemical, environmental and visual, which makes them suitable for specific applications.

The initial design direction included deploying the form-found thin shells directly into the artwork installation. As such beyond the behavior towards heat treatment, post-production durability and cost per sheet we also required high visual clarity. While most thermoplastics can be heat treated, they not all behave similar during. For instance, they melt at different rates which may be easy or difficult to control, and after the process is complete, for instance, they may become brittle or their opacity decrease, see figure 3. We evaluated PMMA, commonly known as acrylic, polycarbonate and amorphous PET (APET). We found the latter being the easiest to treat using a heat gun and quickly cool down using a blow drier, being able to significantly deep draw before reaching its breaking point, while retaining surface smoothness and without wrinkling, becoming brittle or foggy. Perhaps those are also exactly the reason it is the most common material used for water bottles.

The generated APET sheets were deployed for casting white cement reinforced with chopped glass fiber. The water to cement to glass mass ratios were experimentally determined at 15 : 25 : 1 against surface finish and strength characteristics. The presence of 2.4% glass fiber accentuated the glossy finish of the components which in combination with the texture free surface of the APET molds produced

results that resemble highly polished epoxied concrete. In addition, the glass fiber strengthened fine details and component edges which would have been extremely fragile otherwise, see figure 3.



Figure 3. Overview of molding and casting using glass reinforced white cement.

5. Design Tooling

The thermoforming system is comprised of the robotics end-effector, the material positioning apparatus and the electromechanical temperature control system. The initial concept regarding the end-effector was to design a quick change die system using 3D printed stamps. This is similar to conventional vacuum forming fabrication which requires molds upon which plastic sheets are formed. Experiments showed that the thermoplastic materials ABS and Nylon used for 3D printing were not suitable for dies as they deformed after a few applications even though they come into contact with the heated APET for only a few seconds. The next iteration of tool design was informed by the fabrication process of incremental sheet forming which uses blunt tool bits to progressively plastically deform thin sheet materials without removing stock or even heating. The benefit of this process is that it doesn't require the shape of the end product to be transferred from a mold. It is thus less complicated in a number of sub-processes while enabling the fabrication of a wide range of geometries using the same tool. However, while it is more efficient than machining molds for thermoforming, it is also rather slow on per part production as it requires complex tool paths similar to CNC machining. The final end-effector was thus designed to mediate between multiple objectives, namely an increased volume of production, the simplicity of tool building and wide but not total range of geometric freedom. Using a simple blunt tool and by exploiting the multi-axis motion capabilities of the robotic system we were able of producing parametrically varied parts within the same family within seconds, see figure 4.



Figure 4. Left-to-Right: Exploded diagram of jig and development of end-effectors.

The interplay between the malleable plastic sheet and the rigid tool depressed against it produced artifacts not unlike the classical stretched fabric form-finding experiments by Otto. The unique aspect of the process was in the ability to rapidly set up physical experiments; fine tune the control parameters such as the elasticity of the material by heating, loading conditions by the robot motion and boundary condition by the tool shape; easily achieve reproducible the results; and most amazingly being able to obtain robust artifacts after the completion of each experiment. Discovery of those characteristics reoriented our thinking towards experimenting with digitally controlled, robotically fabricated form-finding investigating those artifacts that could perhaps only be generated through our process. We abandoned the notion of producing a conformed shape through a mold or progressively reaching a target surface and let the physics of the material and robot induce it.

6. Parametric Modeling

Integration of the electromechanical components of the digital fabrication system was implemented using Rhinoceros Grasshopper as the parametric modelling platform; Jeneratiff digital design and fabrication library and Python programming language for motion planning, simulation and code generation; and Firefly and Arduino microcontroller for communications and signal processing, see figure 5. The sequence of tasks includes: (1) Loading a sheet of material into the positioning jig. This is performed manually upon which the digital process is triggered. (2) The material is heated on high heat for 20 seconds until it becomes malleable. The Arduino receives a timed signal from the laptop to turn on the heat gun and initiates an internal timer upon which it triggers the robot motion. (3) The robot approaches the positioning jig rapidly, pauses for a few milliseconds to reduce vibration and then begins descending slowly imprinting the material. (4) The heat gun is turned off and the blow dryer is turned on to rapidly cool the plastic. After a few seconds where the material has solidified, the robot motion is triggered again. (5) The arm is removed by playing backwards the same motion and the process can be repeated from step one.

The system architecture is comprised of multiple sub-systems which while individually they perform simple tasks, complexity emerges from their interfaces. The control logic is unidirectional as there were no sensors integrated into the system. Instead, the process is controlled by careful timing upon motions and signals

are coordinated, see figure 6. Design parameters were derived from experiments. The data collected established boundary conditions such as the minimum and maximum amount of time required for heating before initiating forming as well as before causing changes in opacity, the maximum draw depth and twist angle before the material becomes too thin for casting, and the amount of time required for cooling before retracting the tool.

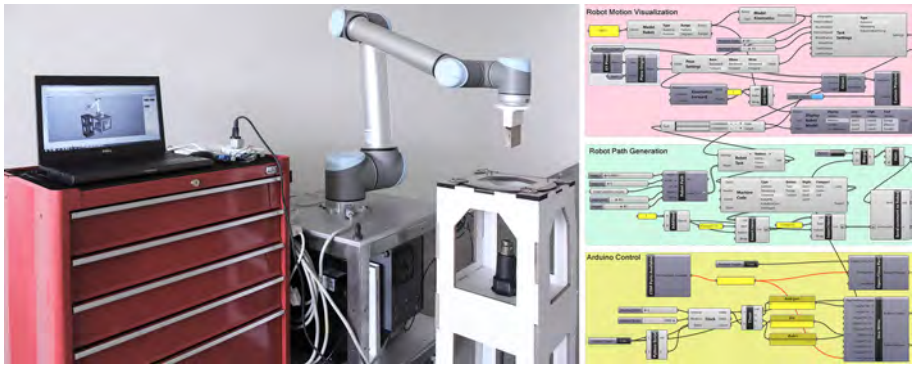


Figure 5. Robot setup and parametric control diagrams.

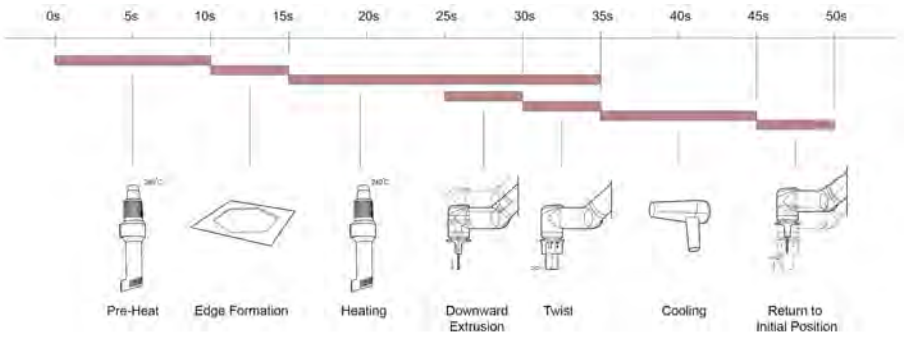


Figure 6. Process synchronization between tasks using time sequencing.

7. Deployment and Installation

The process was deployed for the creation of an installation artwork located on the campus, see figure 7. The design case study offers the opportunity to examine the efficiency and scalability of the process, identify its bottlenecks and limitations as well as fine tune our system towards context specific aesthetic objectives and technical requirements. It is comprised of 280 components arranged in a hexagonal grid. The design pattern was computationally generated using parametric design principles by data mapping. All components use the same tool die but the parameter of draw depth is individually varied based on a global gesture. The variation of profile depth is imperceptible except from certain viewing orientations where the

natural light reveals the overall glyph from the shadows cast. The rotation angle is fixed among all elements to 45 degrees. We found that excessive variation of multiple parameters produced rather verbose outcomes. Instead, we determined a constant angle that produces artifacts upon cursory observation appear simple and consistent; yet upon closer examination, it is evident that they could not have been produced by conventional fabrication procedures as the creases and folds of the cement hint of the impossibility of demolding such forms, see figure 8.



Figure 7. Photograph of overall installation. Photography by Frank Pinckers.



Figure 8. Close up photograph of installation. Photography by Frank Pinckers.

Hexagonal tiles are inscribed in 160mm diameter circle and measure 100mm along the flats with depth from 30mm to 80mm. They weight approximately from 0.5Kg to 1.5Kg which towards the upper range become problematic for support against a flat wall using conventional construction mortars and grouts. We experimented with weight reduction by creating double-sided molds using a pseudo offset APET surfaces produced using the same process and infilling the two plastic layers to create very fine thin shells. The glass reinforcement produced indeed

very lightweight and strong parts. We investigated embedding fasteners and introducing textured patterns on the back side of the castings for mechanical support but this approach also increased the complexity and hence abandoned in favor of directly mounting the tiles on the wall. We experimented high performance adhesives based on polyurethane, epoxy or compositions thereof and after load testing of up to 80Kg in shear, we concluded with a high strength construction adhesive product.

8. Conclusions

Digital design and fabrication technologies such as parametric modeling and industrial robotics through the integration of software and hardware offer opportunities for creative experimentation with material transformation processes in ways which could not have been achieved in the past. Of particular interest to us is the realm of processes that no longer either attempt to map traditional human actions of design thinking and construction into the digital medium or the enforcement of design thought into materiality by powerful machinery such as the design complex forms machined or 3D printed in absence of material integration. Certainly, those are valuable in automation of construction, manufacturing and general engineering but there are opportunities to discover new processes some of which may become the new norm. The concept of deriving artifacts, sometimes driven by aesthetics, sometimes by functional requirements, preferably by combinations thereof, from the interplay of materiality and the formation process is what is inspiring in form-finding. The presented process and case study offer a general approach to thinking and making at the boundaries between physical and digital design.

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Index of Authors

A

Abe, U-ichi 75, 445
Abroe, Brett 169
Agirachman, Fauzan Alfi 23
Ahmadi, Nooshin 529
Akleman, Ergun 767
Al-Qattan, Emad 147
Alaçam, Sema 293
Alonso, Luis 685
Andrade, Marina A. P. 581
Araullo, Rebekah 539
Asher, Rob 715
Austin, Matthew 551
Aydin, Serdar 591

B

Bian, Qiuyi 325
Bissoonauth, Chitraj 863
Bohnenberger, Sascha 841
Borhani, Alireza 377, 767
Browne, Will Neil 387
Burry, Jane 467, 841
Butler, Andrew 715
Buš, Peter 407, 695

C

Cabrera, Densil 853
Caetano, Inês 633
Cao, Yong Kang 663
Cardoso, Carmo 137
Carreiro, Miguel 581
Castelo Branco, Renata 137
Chan, Janelynn 127
Chang, Mei-Chih 407
Chang, Tengwen 521
Chen, Lujie 821
Chen, Nai Chun 685
Chen, Rong 417
Chen, Yingnan 325
Chen, Yutong 893
Chen, Zi-Ru 777
Chirkin, Artem 407
Chirstanti,
Augustine Nathania 23
Choi, Jungsik 603
Choo, Seungyeon 673
Cichocka, Judyta Maria 387
Coorey, Anycie 209, 261
Coorey, Ben 209, 261
Crolla, Kristof 199, 467

D

Dai, Rui 509
Daria, Kryvko 43
Datta, Sambit 521
Di Mascio, Danilo 33
Dickey, Rachel 811
Dounas, Theodoros 313, 863
Dritsas, Stylianos 821, 831, 893

E

Erhan, Halil 127
Escalante, Erik 53

F

Fabbri, Alessandra 53
Feist, Sofia 613
Fernando, Shayani 787
Ferreira, Bruno 613
Fischer, Thomas 179
Fukuda, Tomohiro 85, 95
Fung, Gilbert 127

G

Galanter, Philip 147
Galobardes, Isaac 863
Gero, John S 345
Goh, Yi Qian 893
Gu, Ning 169
Guillot, Romain 53

H

Haeusler, M. Hank 53, 209, 539, 715, 841
Haslop, Blaire 591
He, Yi 417
Herr, Christiane M. 179, 335
Hinoki, Shinichiro 445
Holzer, Dominik 273
Hotta, Akito 75
Hotta, Kensuke 75
Hu, Haojie 325

Hua, Hao 883
Huang, Jeffrey 117
Huang, Jian Ming 437
Huang, Weixin 509, 745
Hwang, Ji-Hyoun 355

I
Ikeda, Hikaru 75
Ikeda, Yasushi 75, 445
Imanishi, Naoki 445
Indraprastha, Aswin 23

J
Janssen, Patrick 303
Ji, Seung Yeul 105
Jia, Tingli 883
Johanson, Madeleine 715
Jun, Han Jong 105
Jun, Han-Jong 623

K
Kaijima, Sawako 427
Kalantar, Negar 377, 767
Kalantari, Saleh 479, 529
Keel, Paul 117
Kensuke, Hotta 445
Khan, Nazmul 715
Kim, Eonyong 673
Kim, Hayan 603
Kim, Mi Kyoung 105
Kim, Mi-Kyoung 623
Kivi, Kaiko 251
Klemmt, Christoph 457
Knippers, Jan 489
Kocabay, Serkan 293
Koenig, Reinhard 407
Koh, Immanuel 117
Koh, Jing Lin 893
Koh, Kendall 831
Koh, Shawn Jyh Shen 873
Kroll, David 169
Ku, Yee Kee 241

L
Larson, Kent 685
Lee, Hyo Jung 231
Lee, Hyunsoo 231, 355
Lee, Jin-Kook 603
Lee, Ju Hyun 365
Lee, Seunghyun 673
Lee, Tat Lin 427
Lee, Yong-Ju 623
Leggett, David 799, 873
Leitão, António 137, 613, 633
Li, Weiwei 655
Liang, Kai-Hsiang 777
Lin, Yuming 745
Liu, Jun 655
Liu, Yuezhong 705
Lo, Tian Tian 63
Loh, Paul 799, 873
Lorenz, Wolfgang 725
Lu, Xiao 863
Luo, Dan 509
Luo, Zixuan 325
Lõoke, Taavi 251

M
Ma, Yidong 499
Matthews, Linda 571
McGinley, Tim 169
Merritt, Timothy R. 757
Miao, Yufan 407
Miyake, Munetoshi 95
Moleta, Tane J. 13, 63
Motamedi, Ali 85, 95
Muehlbauer, Manuel 467, 841
Muraoka, Mizuki 445
Murphy, Matt 169

N
Nagakura, Takehiko 685
Nakapan, Walaiporn 241
Nuraeni, Ruri 23

O
Ong, Lijing 397
Ostwald, Michael J. 365
Ozawa, Yo 23

P
Park, Hyejin 673
Patt, Trevor Ryan 221
Pattanasirimongkol, Apiwat 241
Pelosi, Antony 643

Peng, Zhenwei 655
Perin, Gavin 571
Pita, Juliano 189
Poustinchi, Ebrahim 529
Putra, Andrew Cokro 23
Puusepp, Renee 251

Q
Qu, Tengteng 655

R
Raonic, Aleksandra 561
Raonic, Milos 561
Rasmussen, Troels A. 757
Reinhardt, Dagmar 787, 853
Rodriguez, Edgar 387

S
Saleh Tabari, Mohammad Hassan 479
Sales Dias, Miguel 581
Sare, Tessa 169
Sass, Lawrence 821
Schmitt, Gerhard 695
Schnabel, Marc Aurel 63, 417, 591
Schwartz, Mathew 735
Sharah, Lachlan 53
Shin, Jaeyoung 603
Shinozaki, Michihiko 23
Shireen, Naghmi 127
Sia, Chin Kiat 831
Sitompul, Irene Debora Meilisa 23
Smolik, Andrei 521
Sodhi, Rajat 457
Spaeth, Benjamin 313, 863
Stouffs, Rudi 705
Sun, Chengyu 43
Sun, Zheng 663
Suzuki, Seiichi 489

T
Takami, Yosuke 75
Tan, Rachel 831
Tan, Ying Yi 427
Tao, Peihong 43
Tateyama, Ran 445
Tee, Yong Kiat 831
Tinn, Phil 685
Tong, Ziyu 325
Tramontano, Marcelo 189
Treyer, Lukas 407, 695

W
Wang, Haofeng 335
Wang, Ivy 127
Wang, Ning 417
Wang, Shuo 157
Wang, Sining 199
Wang, Yongsheng 655
Weir, Simon 787
Williams, Nicholas 467
Wortmann, Thomas 283
Wu, Hao 313
Wu, Mingbo 745
Wu, Shuoxian 157
Wurzer, Gabriel 725

X
Xia, Tian 893
Xie, Jenny 685
Xu, Diqiong 43
Xu, Weiguo 499, 509

Y
Yabuki, Nobuyoshi 85, 95
Yan, Wei 147
Yang, Xuyou 873
Yokoi, Kazuki 85
Yu, Rongrong 365

Z
Zang, Wei 655
Zarzycki, Andrzej 735
Zefanya, Teresa 23
Zhang, Bin 655
Zhang, Cheng 397
Zhang, Chenke 313
Zhang, Pengyu 509
Zhao, Yuezhe 157
Zhu, Yufeng 509
Zhu, Yun 655