BEYOND CODES AND PIXELS

Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2012)

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17th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2012)

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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 69 papers that were accepted for presentation at the 17th International CAADRIA Conference, hosted and organised by the School of Architecture at Hindustan University, Chennai, India. The contained papers can be obtained digitally from CUMINCAD (http://cumincad.scix.net) via individual or institutional subscription to CAADRIA (http://www.caadria.org). 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 June of 2011 resulted in the submission of 133 abstracts. These were initially reviewed by the paper selection committee, which invited 124 abstracts for further development. Of these, 85 full papers were submitted to the full paper review stage. Three international reviewers carried out a double-blind review of each submitted paper. Following the reviewers' recommendations, 69 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 Hindustan University, in particular Dr. K. Sarukesi, Vice-Chancellor, who put his full support behind the conference; Mrs. Sheeba Chander, confernece chair and head of department at the School of Architecture, who readily took on the task of organising it; and Mrs. Devyani Gangopadhyay, who worked tirelessly to make this proceedings volume a physical reality. On the following pages, we acknowledge and thank those who contributed to the production of this volume.

We congratulate Mark Burry, who, in recognition of his outstanding contributions to research and education in our field, received CAADRIA's 2012 Sasada Award. In closing, we sincerely thank the CAADRIA community for offering us the honour to serve as members of the paper selection committee for CAADRIA 2012.

T. Fischer, K. De Biswas, J.J. Ham,
R. Naka and W.X. Huang (editors)

APRIL 2012

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BEYOND CODES AND PIXELS

Editorial introduction

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This year, the CAADRIA conference is held for the 17th consecutive year, and – hosted by the Hindustan University in Chennai – for the second time in India. Since the beginning of its history, our community has been utilising computing technology to initiate, trace, investigate and critique changes in bricks and mortar in our physical environments, as well as developments in codes and pixels in our digital environments. The papers published in this volume further testify to the developing and increasingly demanding standards of research and production that characterise this history. Recent attention to fabrication, for example, gives fresh recognition to kinds of rigour other than scientific and formal ones. Beyond bricks and mortar, and beyond codes and pixels, however, CAAD research and education offer more than tools and test beds for changing our environments with technical means and according to external standards.

The purpose of changing our external environments, according to the principle of homeostasis, is to ensure our internal stabilities. We adapt our surroundings to meet the needs of our insides. For the majority of the human population, establishing and maintaining livable contexts depends on having biological offspring, which leads to considerable population growth in both rural and urban contexts. Technology, too, offers us powerful capabilities to alter environmental conditions, again with a patchy record of sustainability. Our ability to predict whether some alteration of our environments will prove to be desirable in the longer run, or not, is in need of catching up. New practices that initially seem desirable and successful oftentimes develop into proportions that entail considerable penalties. Meanwhile, technology gives us ever-increasing capabilities to monitor our environments, and to mass-communicate the many alarms thus gathered. Thus, in our attempts to improve our environments, we learn to expect and to fear our individual, as well as our collective demise. With such fatalistic perspectives comes a desire to secure one's footing in the world of images and symbols in which we primarily live (Pask in Bateson, 1972, p. 309). While those operating in academic and designerly fields may feel sure of our own footing by creative activity, the majority of us resorts to producing the biological progeny that guarantee this footing (Pask ibid.), further fuelling human proliferation.

Do we have viable strategies for purposeful action to address these challenging states of affairs? How successful have we been so far at utilising design and technology to improve the livability of our environments? How successful can we expect to be with these approaches in the future? What can we expect of academic associations and conferences that aim at improved environments by way of purposeful applications of technology?

Gregory Bateson warns of encounter groups in which clarity and the capacity for self-criticism are lost in the search for emotional communion. He argues that groups of these kinds, including most conferences, make the kind of shortsighted decisions or elaborate the kinds of epistemologies that endanger the world (Bateson, 1972, p. 305). What do a CAAD research association and its annual conferences have to offer besides ever-specialising scientific and technological answers to well-understood questions – in a justifiable proportion to their consumption of jet fuel?

What if we use technological and scientific insights not only to adapt our external environments to the needs of our internal environments, but also the other way around? And what if our accomplishment of change around ourselves is taken as a metaphor for accomplishing change within us? Can we imagine a mirror plane through which our doing and our learning are meta-

phors of one another? And can we imagine rigorous standards of our thinking and acting to be fostered not only on the objective and moral outside, but also on the subjective and ethical inside? Bateson (1972, pp. 285ff.) suggests that everyone is his/her own central metaphor. In this way, it can be argued that we and our research field are metaphors of each other. "In every age", Young (1959, p. 14) argues, "men speak about themselves and the world around them partly by making comparison with the tools that they use. Conversely, they describe the actions of their tools by speaking of them as if they were men".

Speaking of ourselves in terms of our tools, according to Pask, offers a way to address questions regarding our footing in history, stresses caused by there being more and more humans as well as fears of individual and collective demise. Pask challenges the notion of the individual as "one head". Instead, he points towards our favoured ideas and ways of acting as that which we may wish to reproduce and regard as our progeny. Pask offers the metaphor of the general-purpose computer for the human brain, and that of classes of programs for our favoured ways of thinking and acting. With one "computer" being capable of running instances of multiple "programmes", and with "computers" being capable of replicating "programmes" of other "computers", one's footing in history is, according to Pask, no longer directly dependent on biological progeny. It is not necessarily a matter of making more "computers", but one of getting one's "programmes" started in other "computers" which will run beyond one's own runtime. In this view, CAAD research, CAAD education, and the concerns for one's personal footing in history are inseparably interwoven. Which ideas and ways of acting are to be considered and promoted in the absence of technical certainty? This is the search for an essential class of "programs" capable of choosing wisely between commitment and detachment (Bateson, 1972, p. 305) according to given circumstances.

In this volume, several authors refer to external phenomena and techniques as metaphors for adjusting internal thought and appreciation. For example, Roudavski (p. 659) likens his pedagogical approach to vision tricks in life drawing, since both practices combine available techniques opportunistically according to the circumstances, with the aim of amplifying understanding. Karakiewicz and Kvan (p. 151) describe how metaphorical diagramming in digital environments allowed their students' attention to be shifted to the relationships between elements. Ambrose (p. 699) and students develop potential metaphorical relationships between the human body and architecture, which demands alignments or resonances between architecture's physical and mental constructs.

Such discussions call for a discourse that reaches beyond codes and pixels to acknowledge the mutual metaphorical connections that can be drawn between our external and internal environments, with a view to exerting desirable changes not only in our external environments, but also to adjust our internal ambitions wisely, according to internal and external cues.

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RATIONALISATION OF COMPLEX BUILDING ENVELOPES

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Abstract. Rationalisation of architectural geometry is paramount to a design's manufacturing and construction. This paper presents a methodology of pre/post rationalisation of building envelope geometry using statistical computation.

Keywords. Rationalisation; optimisation; geometry; computation.

1. Introduction

Rationalisation is the process of information reduction or compression of an architectural design with the goal of simplifying and optimising its geometry towards manufacturing and construction. Building rationalisation shares common goals with value engineering. However, rationalisation is both a qualitative in as much as quantitative process. Thus, it is a core architectural responsibility rather than a cost management exercise, and as such, a process of design in as much as a process of analysis. Architectural rationalisation aims at the control of quality from detail design to a building's construction phase as well as gains in building performance in term of material resources use, manufacturing time and labour expenditures.

This paper studies the process of building envelope rationalisation using statistical computation methodology of optimisation as means for addressing the problem of varying geometry in contemporary free-form design. The aim of this paper is to: (a) Discuss methods for understanding, determining and addressing design complexity (b) Review two theoretical frameworks for design rationalisation: the pre-rational and post-rational design principles, illustrate their benefits and limitations and demonstrate their meeting point and (c) Propose an integrated performance-oriented model for analysis and design for building envelopes, using digital design technology.

2. Design complexity

Design complexity is a difficult notion to discuss in absolute terms as there is no single metric that entirely captures it. We can employ for example a design's inputs or outp uts as complexity indicators; for instance, geometric complexity or the absolute size of parameter or solution space. In this paper we use a functional definition of complexity composed of three indicators: (a) Predictability: the insight a design system may offer as its capability of revealing the critical points of complexity escalation (b) Compactness: the degree by which a system can capture design rules and exceptions with a limited number of parameters. (c) Reliability: a system's capability to ease the verification and communication of its state. We feel these indicators are expressive of the procedural qualities of a system rather than merely its quantitative characteristics.

While a rectangular-grid curtain wall system implicitly ensures all of the above criteria, a free-form envelope does not offer the same guaranties. The only certainty is that there will be ranges within building dimensions vary. This becomes a significant problem for contemporary architecture and its construction as it raises questions about a responsible and cost effective use of natural and human resources. The aim of our methodology is to assist in assessing complexity, rationally evaluating the costs and benefits of a design and taking positive steps in optimising its construction.

3. Related work

There are two contemporary methodologies of architectural rationalisation within the context of digital design: the principle of (a) pre-rational and (b) post-rational design. Both have been extensively discussed by Shelden (2002), Glymph et al. (2004), Whitehead (2004), Hesselgren et al. (2007), Ceccato et al. (2010). The pre-rational method is founded on the proactive application of logical constraints and the expression of design as a process of interpolating composition of geometric primitives, such as lines and arcs, quadratic and developable surfaces. Those are known to exhibit desirable properties (Leopoldseder and Pottmann 2003, Hoffmann and Kocacs, 2004, Pottman 2007) which may simplify construction. The post-rational method is a functional approach, in the engineering systems notion, towards architectural rationalisation. It is heavily based on the use of design metric analysis and iterative optimisation processes of design and computation. The critical assumption made is that design is an input and it is retrospectively approximated to a rational model up to a notional design intent error tolerance. Optimisation strategies for building structures and envelopes have been demonstrated in the past by Williams (2001) as well as by Luebkeman and Shea (2005).

4. Geometric description

We investigate a prototypical rationalisation exercise of a complex building envelope optimising its geometric properties towards visual, manufacturing and construction constraints. Our system is composed of three components: (a) Geometric description using parametric design principles (b) Analysis using metric performance criteria (c) Optimisation using statistical methods. Our goal is to design a curved wall in plan and section; a generic description for a free-form envelope. We express this geometrically by employing a pre-rational strategy of a piece-wise circular tangent arc sweep surface (Figure 1), also known as translational surface (Schober 1999). The result envelope belongs to a family of surfaces exhibiting certain desirable characteristics: (a) Components are linear and circular arc segments which are simple and offset without degeneration (b) Discrete surface patches along the surface's primary directions are planar quadrilaterals and the envelope is developable (c) Visual constraint of tangent continuity is ensured by definition.

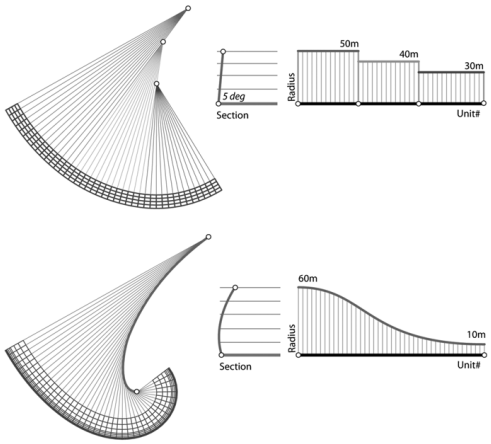

Figure 1. Rational envelope definition as a function of radius.

Parametric design with pre-rational envelopes entails defining a chain of explicit geometric relationships between the radii of consecutive arcs such that at the transition point both arcs share the radial vector but not the same magnitude (Figure 1). A sectional profile may be swept along the base path to generate the envelope. Our implementation expresses planar geometry as a function of curvature, instead of individual arcs, such that we can span a wide range of free-form geometry. We achieve this generalisation by a mathematical composition of the basis rational function with a NURBS curve geometry

graph. The planar section may be of arbitrary complexity without violation of the said geometric properties. In similar fashion we may also parameterise the spanning angles/chords such that we can increase resolution density at façade regions of high curvature.

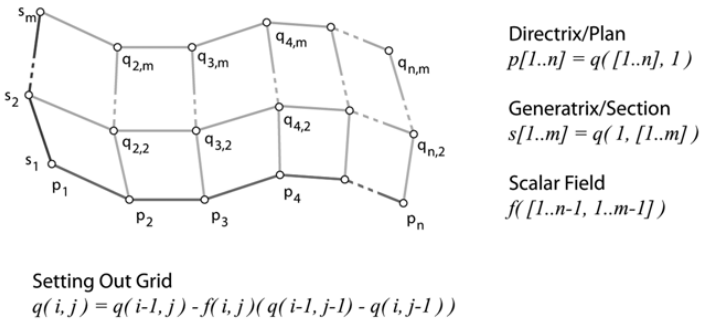

Figure 2. Recursive definition of rational envelope determined by linear displacements.

Radius/chord parameterisation is capable of spanning a large range of pre-rational envelopes containing both discrete and continuous curvature characteristics. An important limitation of radius-driven geometry is that it becomes numerically unstable at planar or near planar wall regions as radial vectors become parallel and radii approach infinity. This shortcoming may be mitigated by employing an alternative rational basis function using linear combinations of displacements instead of radii (Figure 2). The definition is comprised of a planar scalar field, a directrix curve in plan and a generatrix curve in section (Dritsas and Becker 2007). Both curves may be of arbitrary geometric complexity without violation of the desirable rational properties. Displacements are directly related to the physical dimensions of envelope's bay sizes which are guaranteed to remain within numerically stable limits. A typical cladding bay size for instance does not exceed a few meters due to architectural and manufacturing constraints. While this definition is more versatile it is also more complex as the scalar field, a 2D matrix of bay sizes, is more cumbersome interacting with compared to the radius/chord graph.

5. Metric analysis

Setting out geometry spans large regions of a building's envelope and requires subdivision into smaller components which can be manufactured using standard shapes. If the arcs' radii are large enough they may be approximated by

linear segments without visual distortions (Figure 3) such that manufacturing costs of bending can be eliminated. There exists no objective metric determining when this simplification is acceptable, as it is bound to visual preferences, fabrication constraints and cost control considerations. However, as a general rule of the thumb shallow arcs of sagittal lengths of a few millimetres may be linearised with nominal errors.

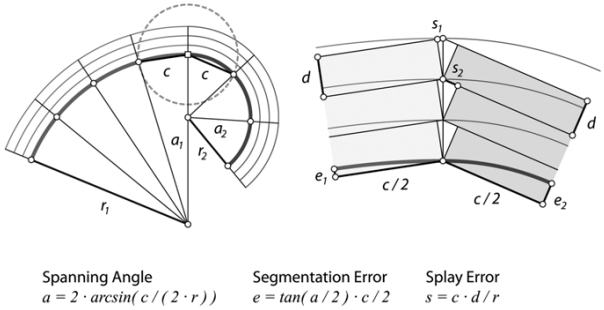

Figure 3. Geometric principle and expressions of approximation errors.

An additional constraint at the phase of segmentation is often imposed by the desire to control the total number of dimensionally unique parts; a logistical and cost control consideration as large volumes of varying parts increase manufacturing and assembly time and also encumber the process of building information management. It is thus reasonable to attempt reducing variations by using a single or small number of notional cladding unit sizes. There exists two common segmentation strategies: (a) Using a single chord length to greedily subdivide every arc of every level and accumulate errors at the start/end of each (Hesselgren et al. 2007) (b) Using a single chord length at the base of the setting-out and allowing each level a unique type per arc such that errors are distributed between units.

Our system employs the later strategy and in specific we use a fixed chord length for determining each base arc's total spanning angle. In this fashion transitions between arcs occur exactly at the end/beginning of a unit and every segment belongs exclusively to one particular arc instead of spanning across two. The aim of this constraint is to eliminate angular errors induced per level and special unit types required to span transitions had we allowed segments to span across arcs.

We further observe that a chain of linear elements along an arc suggests that each joint between segments is mitred at the bisecting angle $a/2$ which indi-

cates that for each arc there is a unique type. For transitional segments between tangent arcs of different radii there are additional types as the bisecting angle varies laterally. For mitigating manufacturing complexity these angles are averaged or squared to 90 degrees, such that additional time and cost is reduced. This approximation induces a particular visual artefact, commonly known as the splay error; whereby small gaps can be occur between consecutive segments (Figure 3). There is no general consensus as per when splay may be ignored or introduces significant visual nuances in a building's appearance. In the case of a tall building's envelope for instance, splay artefacts become of lesser concern proportionally to an observer's distance from the ground level. In practice, a common rule of the thumb is to ignore splay errors when they remain below typical architectural detailing and/or manufacturing tolerance. For example 10 mm splay error is within an acceptable range since even planar walls exhibit this dimensional range of detailing between joints.

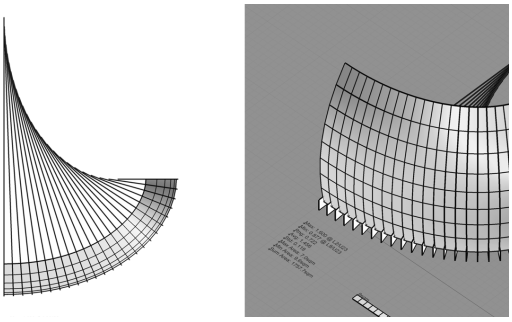

Figure 4. Interactive visualisation of envelope performance metrics.

Our design and computation system provides interactive performance feedback via direct visualisation of dimensional as well as error metrics onto the design envelope (Figure 4) such that design and analysis become unified rather than sequential and disjoint tasks. Schematic design and construction implications thus merge intuitively as bridges across three levels of detail, namely setting-out, zoning and detailing, are established. Free-form design becomes creative while informed.

6. Design optimisation

Our final step in rationalising the envelope's geometry attempts to further reduce dimensional variation. We note that we cannot improve on the total unit number without drastically simplifying geometry to a smaller number of radii in plan and/or a simpler section or alternatively without introducing

new approximation errors. A degree of freedom we may exploit is to attempt compounding additional errors within existing. For instance, it may be more desirable to constraint a unit's size rather than its splay error. Allowing errors to vary may permit clustering units by length increments and in return reduce the total type number required to span the entire envelope.

Identifying a discrete number of unique types that best approximate variation among a set of samples while bound by an error metric can be seen as a data clustering problem. In particular it is an NP-hard problem that can be solved via numerical approximation (Jain et al. 1999). As a benchmark we employ a basic fixed-increment distribution strategy in order to understand the qualitative aspects of our problem but also compare and contrast alternative clustering strategies. We define a unit increment step-size of for example a few millimetres, we then round elements down to their nearest cluster, measure the average and maximum errors and count the number of non-empty or unique types (Figure 5). The maximum rounding error in this scenario is bound by the predetermined cluster's size, while the average error is approximately half of that. The process is efficient to implement yet far from optimal in finding the best cluster partitions as it disregards the density characteristics of the original probability distribution.

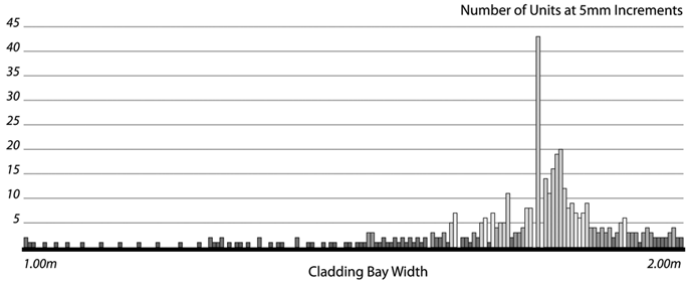

Figure 5. Unit type distribution of continuous radius function envelope.

For selecting better cluster pivots we developed a constrained k-means algorithm (MacQueen 1967). K-means clustering is a statistical method for minimising intercluster variance. The process selects randomly a number of k-cluster partitions, associates each element with its closest cluster and repositions the partition centres at the mean of each cluster's elements. The algorithm converges after a few iterations and it is sensitive to the initial seed-cluster locations. Our application employs a modified k-means method because we cannot allow units to increase dimensions up to their nearest cluster; expanding units would result to geometric clashes on the envelope. Instead, we pin one

cluster to the lowest bound of the initial distribution and skew the final cluster's positions to their individual lowest bound. While the modification challenges the distance metric of the original algorithm it still performs on average 11% and 35% better than the benchmark strategy in terms of maximum and average errors, respectively (Figure 6).

While k-means improves intercluster error it cannot address the problem of minimising the maximum error which is visually more pronounced. A qualitative interpretation may suggest that minimising the maximum error expresses the desire of controlling the largest visible gap across an envelope while minimising the average error implies that rounding transitions need to be as smooth as possible. In order to minimise of the maximum intercluster error we employ the k-tMM strategy (Gonzalez 1985). The algorithm splits an initial cluster containing every envelope unit into sub-clusters while maintaining the said criterion. Each unit is rounded to the lowest bound of its cluster. The algorithm deterministically converges within two times the optimal solution (Gonzalez 1985). Our implementation achieves on average 16% and 50% better than the benchmark strategy in terms of maximum and average errors, respectively (Figure 6).

Overall, we achieve improved results with both alternative min-average and min-max strategies compared to our initial benchmark strategy. In terms of complexity k-tMM is simpler to implement, it runs faster, it is much more predictable and yields better results for large cluster sizes in terms of both maximum and average errors perhaps due to k-means modifications that skew what should have been a symmetric metric. However for small cluster sizes the randomised nature of k-means achieves better results than k-tMM.

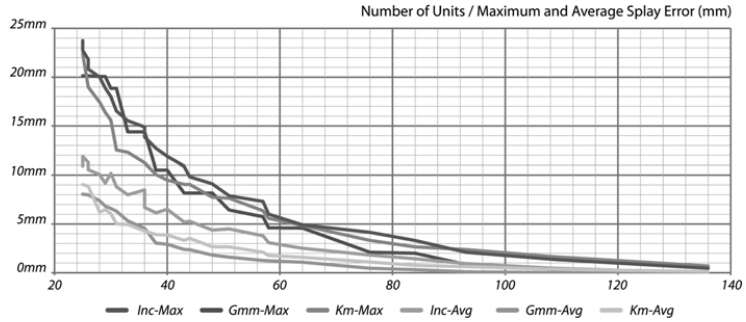

Figure 6. Maximum and average errors of clustering strategies.

7. Discussion

In conclusion, our case study makes a series of assumptions and follows through one of the multiple decision making trajectories available during the

process of envelope rationalisation. As we cannot exhaust the entire range of design permutations we offer instead a strategic thought map comprised of three domains: (a) Schematic: geometric definition of the design envelope (b) Detailing: design decomposition of an assembly into components and identification of performance metrics and (c) Construction: mediation of visual and manufacturing considerations via optimisation methodology.

Our notion of design rationalisation as a process of design information compression touches the topics of: (a) Operations: the reduction of design variance in free-form building envelope and as a result achieve gains in the ability to control of quality over cost, and (b) Design thinking: structuring design relationships via pre and post rational modalities in an expressive yet compact process that assists gaining insight in critical design factors and in turns leverage overall design complexity. (c) Design computation: present an integrated design and analysis method where schematic design bridges across to construction considerations; thus transforming those traditionally sequential and remote phases into an expressive while informed process.

On the domain of operations we presented a study of creating typology clustering of variable building parts via statistical method. The contributions of this study are in (a) Defining relationships between quantitative metrics, approximation errors, with qualitative assessments, visual appearance (b) Offer tools for cost/benefit analysis by expressing typology as a function of error; or in other words cost as a function of visual performance. Using this approach we may select a limiting visual threshold and derive the number of units and cost, and vice-versa, or seek equilibrium optimisation whereby the marginal error equals the marginal cost.

In design thinking we selected an indicative path of employing pre/post rational methodology according to aforementioned complexity assessment criteria of predictability, compactness and reliability. We chose pre-rational approach to schematic and detailing analysis while in construction we engaged into post-rational methodology. Our principle was to select which ever strategy was most effective towards said criteria per task identified and addressed. Pre-rational analysis allows us to decompose design into simpler parts and nest considerations in linear manner via simple geometric concepts which are familiar to the architecture language. Those are relatively easier to mentally trace, gain insight, make educated guesses and communicate. Post-rational analysis while capable in addressing far more complex problems it has a steeper learning curve as it requires abstract mathematical, statistical and computation concepts which have very different rules of composition than traditional architectural methods. We conclude that both strategies are inherently inter-dependent even though they appear approaching the same subject

from opposite directions. We could have not solved the typological clustering problem directly without approximation for instance. Meanwhile, we may replicate the descriptive methodology to approximate an existing spline design envelope in addition to measuring deviations and/or clustering components towards both dimensions and curvature metrics.

In the future we will explore a rationalisation process with bias on post-rational design principle to assess the process pros and cons in greater detail. We would also expand on meta-heuristic analysis of cost/benefit of design to construction optimisation via economic equilibrium theory.

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AUTOMATION AT SCALE

Geometry, analysis and post processing

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Abstract. Our team is currently engaged in the peer review of a large steel stadium dome roof. The roof has a diameter of approximately 300 m and rises to over 70 m in elevation. In addition to its size, the roof also contains a moveable component which can be deployed during inclement weather. The roof structure comprises of approximately 32,000 beams with 10,000 nodes. This paper overviews our efforts in scaling digital design techniques with regards to automation and parametric geometry to expedite the verification of structural members and geometrically complicated connection nodes. The paper will discuss two realms where automation was deployed. The first realm is the verification of Type 1 node connections where less than eight members intersect at a single work point and is relatively geometrically simple. Type 1 nodes were checked against published code requirements. Type 2 connections consisted of nodes where more than eight members intersected or bracing angles did not meet code guidelines. Type 2 nodes were verified using the finite element method and large scale automation of node geometry creation to structural analysis post processing was employed.

Keywords. Automation; Rhino 3D; scripting; structural; database.

1. Project overview

Our team is currently engaged in the peer review of a large stadium steel dome roof. The roof has a diameter of approximately 300 m and rises to over 70 m in elevation. The covered surface area of the stadium is approximately 71,000 m^2 and will have a seating capacity of approximately 55,000. Since the stadium is located in an equatorial country, the roof contains a moveable

component which can be deployed during inclement weather. The fixed roof component contains approximately 16,450 beams and 5350 connection nodes. The movable roof component contains an additional 16,155 beams and 4,200 connection nodes.

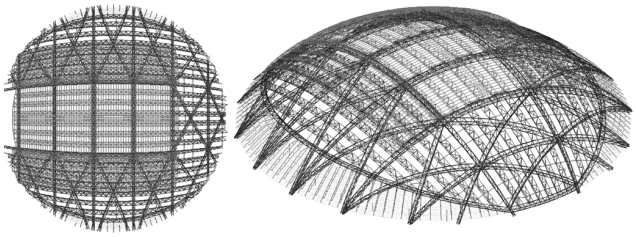

Figure 1. Roof wireframe geometry.

According to country building requirements, all building projects must go through a round of peer review to verify the adequacy of the structural design. From a workflow perspective, our team receives documents (wireframe geometry, excel sheets, sketches) from the design engineers and uses these in our review efforts. Fragmentation of information was a major obstacle in the project since all information was received from third parties.

2. Project innovations within the context of digital architecture

Conferences such as ACADIA, CAADRIA and SmartGeometry consistently highlight the work of academics and practitioners that push the boundary of digital design and workflows. However, much of the published work is often rooted in the realms of sculpture and novel fabrication processes. As the practice of digital architecture has spread in the profession, there have been heated dialogues about the relative emphasis on the novelty of the process over the final product (Gage 2011).

Multiple papers discussing real world projects have illustrated the challenges and limitations of inter-office and inter-discipline digital design workflows (Miller 2010, Rolvink 2011, Hladik 2011, Chok and Donofrio 2012). Sharples (2011) illustrates the complexity of engaging in a digital workflow in live projects with constantly shifting needs and client demands. This paper continues this discourse by exploring the challenges and limits of executing digital design workflow propositions from the theoretical realm with a professional team having varying levels of digital design experience. The adjustments from theoretically optimised workflows to practical implementations are also discussed.

3. Geometry overview

The stadium roof is framed by circular hollow sections (CHS) of varying diameters and wall thickness. The first stage of geometry set out and structural analysis was performed using centreline wireframe geometry. Beams are modelled from work point to work point with no adjustments for final connection geometry. In the checking and design of the node connections, the tube cut geometry and adjusted setting out had to be established. The largest geometry difference from the global analysis wireframe model and the local connection geometry was the introduction of the node can. A node can is a thickened zone across the truss chords to receive the incoming brace members. This is shown in Figure 2.

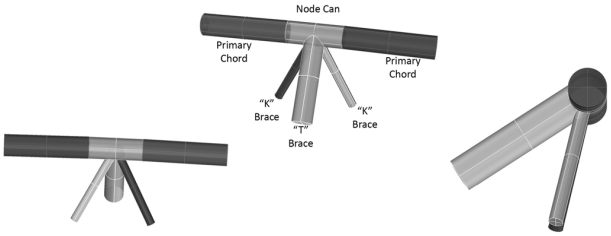

Figure 2. Node connection piece definition.

4. Node connection types

According to the design code, node connections can be classified into a few types. K gapped, K overlapped, X and T connections. This is illustrated in Figure 3. When the wireframe geometry deviates from such simple geometry, finite element analysis was required to verify the adequacy of such connections. In situations where secondary framing members were of similar diameter as the can, re-alignment and kinking of members was necessary to set out the braces correctly (Figure 4).

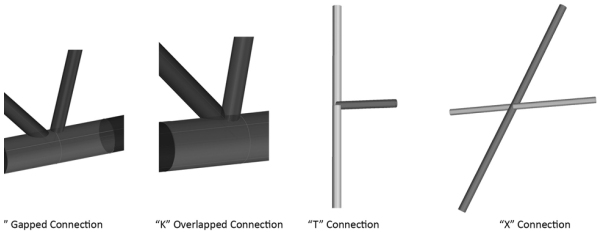

Figure 3. Typical "simple" connection.

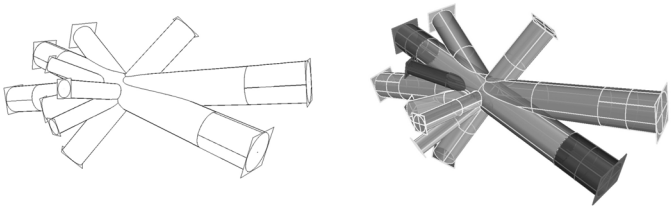

Figure 4. "Complex" node connection.

5. Project challenges

The project began with a relatively simple exercise of calculating relative brace angles to support the existing review teams' efforts. This was done through interoperability between a structural analysis package (Strand7) and Rhino (Figure 5). However, as the peer review efforts got underway, the sheer number of node connection configurations and management of structural analysis data set required re-thinking of the scalability of the existing workflow which the team was embarking on. The most significant challenges are overviewed below.

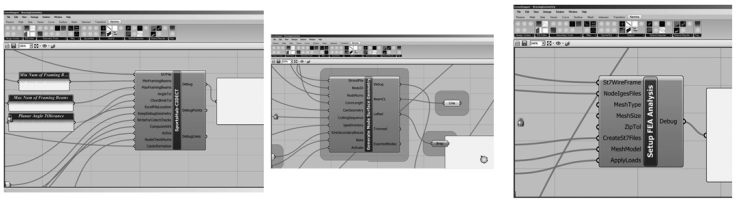

Figure 5. Project workflow.

5.1. LARGE STRUCTURAL ANALYSIS RESULT DATASET

Structural analysis generates an incredible amount of data and fortunately, the result set scales linearly with the number of members. In the roof, the team had analysed eight different global models. Each model comprised of approximately 32,000 beams. While traditional spread sheet and desktop database (MS Access) approach might have been sufficient for regular sized projects, the final analysis result dataset in this case was much too large for such approaches (>25,000,000 rows). Furthermore, the team needed the ability of actively query the result set in preparation for code based design checks. To meet this need, the team migrated the result set from the structural analysis package to SQL Server 2008 R2.

5.2. GEOMETRIC COMPLEXITY

The doubly curved nature of the roof structure meant that no two connections on one side of the symmetric axis (x-axis) were completely alike in terms of relative brace angles and set out. This required a workflow that could robustly perform the following.

1. Compute relative brace angles
2. Identify primary chords and can direction
3. Compute the approximate length of the can required
4. Classify the connection into design code configurations for spreadsheet based checks
5. Identify overlapped or gapped conditions
6. Generate and export surface geometry for FEA analysis

6. Type 1 automation

There is always a need to compartmentalise and develop workflows in parallel in all large projects. While scripting/programming of all design code based design checks would have been more seamless, this approach disregards the varying digital design skill level and unease with deviation from traditional engineering practices (spread-sheet based checks). A two tiered approach was thus adopted.

First, all geometry work such as brace angles, tube-tube intersections, gaps and overlaps were computed in a custom Rhino-Grasshopper component. The inputs to this component were the reference wireframe geometry, variation to base geometry (tube thickness etc.) provided by design and other geometric tolerances for classification. This is shown in Figure 6.

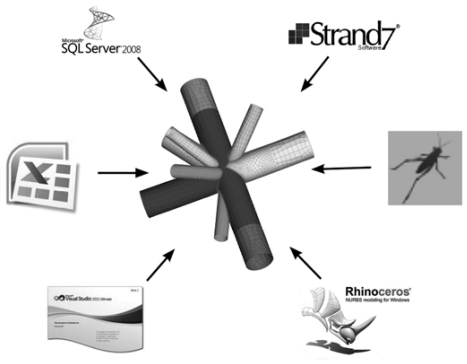

Figure 6. Custom Rhino-Grasshopper components.

The component does geometric calculations on the reference wireframe and also queries the central SQL Server database to extract envelope beam forces for design checks. A platform neutral comma separated file (CSV) is generated from this script and used as input for code based design checks.

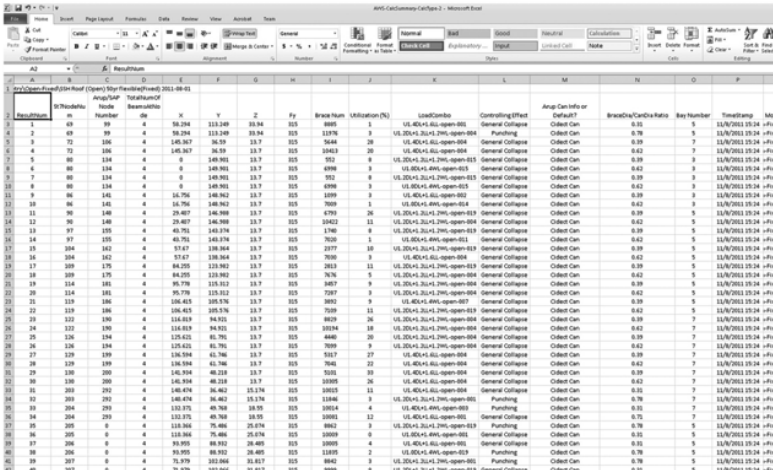

Figure 7. Sample of CSV file generated from custom Rhino-Grasshopper component.

In other design code based checks where individual beam forces had to be used, as opposed to envelope forces, generation of CSV files for design checks was impractical. This approach would have potentially led to more than five million (5,000,000) rows of design code checks and been completely unmanageable with standard spread sheet approaches. For these checks, the team programmed a self-contained design code check component.

The script would perform the design code check on a particular node under all load cases (128) and report only the most demanding load case. Using such an approach, care had to be taken in managing the workload on the database. In the early phases of this custom component development, server side database timeouts and client side "out of memory exceptions" were common. While such issues would likely have been avoided with professionally trained programmers, the lack of formal programming and IT training started to show its limitations here.

As with all script development, testing and debugging was done on a representative set of connection nodes. However, when the design check routine was applied to the whole roof, different strategies such as batching was needed to reduce the demand on the database.

7. Type 2 automation

Type 2 automation refers to situations where code based design checks were inadequate. For example, code based design checks reduced bracing configurations into relatively simple sets of "K", "X" and "T" types. In some locations where there were complex brace-brace intersections, finite element analysis needed to be used to evaluate the adequacy of the design.

Finite element analysis takes significantly more time to set up, run and post process. In this project, setting up of the finite element analysis model required the trimmed brace surface geometry which was created from the baseline strand wireframe geometry. The wireframe was adjusted to include the introduction of the node can and any other offsets to account for the final set out geometry (Figure 8).

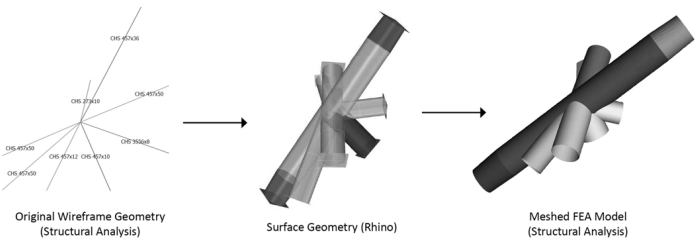

Figure 8. Conversion of global wireframe model to surface geometry.

The node connection surface geometry was created through another custom Rhino-Grasshopper component which set all the surfaces to a comma separated layer name which facilitated transfer of information to the structural analysis package Strand7 (Figure 9).

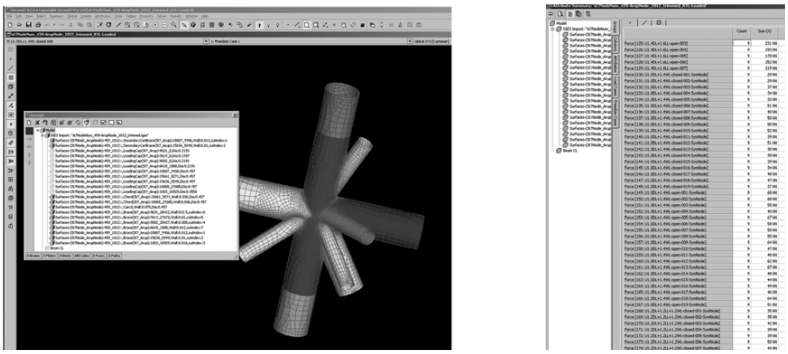

Figure 9. Finite element model screenshot and loading table.

Once the geometry was set and meshed in the structural analysis package, another level of automation was used to create rigid clusters and apply loads. For each connection node, a total of 256 load cases needed to be applied to each individual brace and performing this operation manually would have been error prone and time consuming. The loading information was extracted from SQL Server and applied to the model via script. Figure 10 shows the final stress analysis of a complex node.

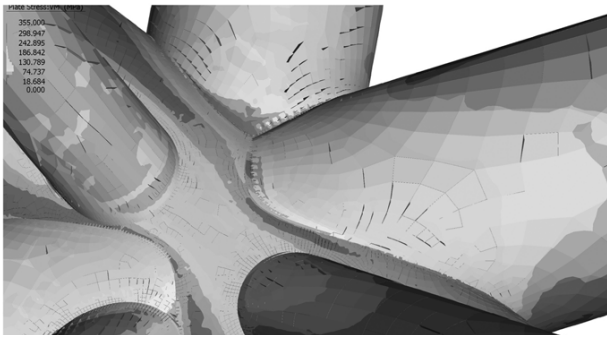

Figure 10. Screenshot of FEA analysis.

8. Scalability of the process

As previously discussed, all testing of code, database procedures and scripts were tested on a small representative set of nodes. However, scalability issues arose in two arenas. The first area was the post-processing of the forces on the connection on an individual load case basis. The other was the management of the large finite element models and its results.

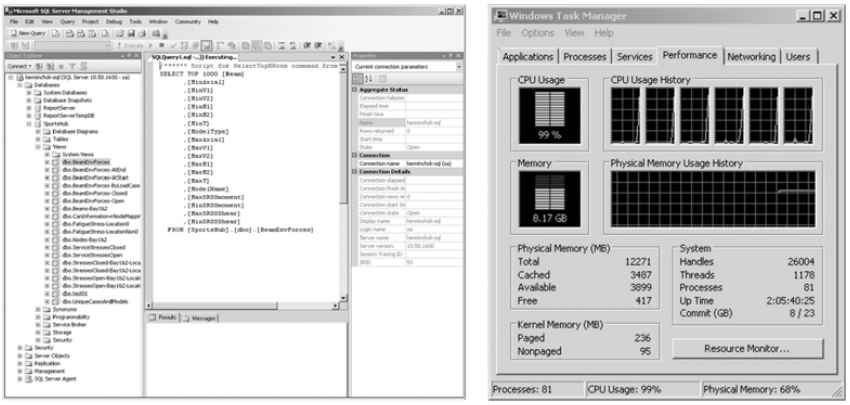

Figure 11. Computing loads on SQL Server

The first was the processing of the connection strength checks on a load case by load case procedure. The loads on the database through repeated queries had to be programmatically managed by batching and other throttling strategies. A typical load on SQL Server when the routines were running is shown in Figure 11.

The second challenge with scale was management of the pre-processing of the finite element models. With any CAD import/export operation, inter-operability and translation is always an issue. Coupled with the finite element meshing, some "cleaning" need to be performed to ensure the final analysed finite element mesh was geometrically close to the original surface geometry. A meshing problem which arose is shown in Figure 12. A custom routine was written to project the nodes back to the original tube surface. However, the issue of scale surfaced here as well.

While the simplistic approach of loading all the finite element nodal coordinates into memory when the models were smaller (<30,000 elements), this approach did not work on the larger models which contained over 100,000 plates and 200,000 nodes. To get around run times and memory limitations, the bounding box of the finite element model was "divided" into cubes and a zonal approach was used to adjust the nodes back to the original surface. Later in the project, a multi-core approach was also deployed to adjust the models as quickly as possible.

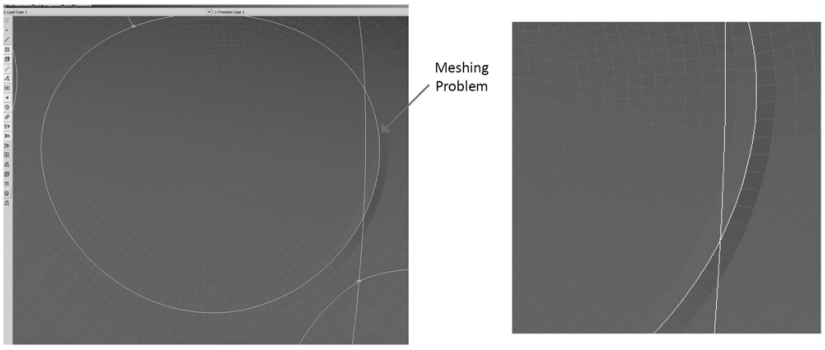

Figure 12. CAD translation/meshing issue.

9. Summary

This paper has explored the team's foray into the scaling of programmatic approaches to geometry and structural design. In projects of typical scale, self-taught programmers in the architectural/structural realm do not usually have to worry about run times, data storage, memory limitations or varying

skill levels. However, such considerations unexpectedly became the main challenge in this project. The paper has discussed our team's challenges and strategies to deal with the issue of scale and deployment of digital processes as algorithmic architectural and structural design approaches become more prevalent in the built environment.

Acknowledgements

The author wishes to acknowledge the efforts of the project team that has bravely incorporated new and untested digital design processes into their workflows under immense external time constraints.

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A HOME DESIGN SYSTEM BASED ON COMPONENT REUSABILITY

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Abstract. This paper proposes a computer-aided design system for modular houses, focusing on component reusability. By resolving user-designed house layout into its component elements, and producing lists of reusable elements and those necessary to purchase, the system assists users in need of making design changes in their modular house. The application of the strategies described here may reduce human efforts in complicated process of re-arranging components according to new layout design and help to increase the reuse of module components in practice.

Keywords. Modular house; component reusability; home remodelling; user participation; computer-aided design system.

1. Motivation

In architectural field, sustainability issues that aim to save resources, reduce waste, and provide high quality living environment at the same time have recently become the centre of public attention. Unfortunately, however, demand for high quality of housing inevitably leads to frequent house renewal that involves layout adjustments to properly respond to the various and changing needs of the tenants (Kumagai 2002), which makes high quality of house performance and resource saving difficult to coexist. As an effort to avoid the conflict, there have been many studies on new structure systems and functions of the residential building with both durability and adaptability, and Open Building System is one of them. Distinction between structure parts that we refer to as ‘support’ and changeable building parts called ‘infill’ provides customisable non-structural part of building based on residents’ lifestyle and makes replacement of materials possible. (Kendall and Teicher 2000) Not only

has the advent of Open Building System lengthened life span of buildings, but it has also introduced Modular Construction, a promising way of providing the customisable infill. A large portion of research has discussed that the use of modular construction provides many significant advantages, including: 1) save on overall project schedules, 2) improvement of quality, 3) increased onsite safety, 4) the reduced need for skilled workers on site, and 5) a decrease in the negative environmental impact caused by construction (Lu and Korman 2010). Moving in direction of modular construction, housing module components have been developed by diverse companies and research institutes including PANEKYO, NEXT21, Daiken Corporation, and Korea Institute of Construction Technology (Lee and Kim 2010). Although non-structural and changeable space of residential building and module components to fill it meet the physical qualifications for flexibility in housing, user-participatory design changes are not very common. This paper defines the absence of a tool that supports pre-project planning and component coordination as reason why residents in modular houses have difficulty in participation, and believes that aid of computational tool is helpful to overcome the challenge.

The purpose of this study is to investigate the possibilities of user-initiative design change in modular houses and to improve computer-aided design system for modular residential buildings. In this paper, framework of the system is presented with necessary functional specification and illustrated with a case study using housing components by Korea Institute of Construction Technology as an example. This system could be used by expert or by non-expert, but in both cases, it may reduce human efforts in complicated process of rearranging components according to new layout design and help to increase the use of module components in practice.

2. Background

Excess of the house supply ratio has brought about a transition from a supplier-oriented environment to a customer-oriented one in housing market in many countries of Asia including Korea, Japan, and Taiwan. Additionally, since customers became to consider their various needs and the quality of housing more important than they had done, house customisation is inevitable to meet the various needs and to ensure competitiveness in the customer-oriented housing market (Shin et al. 2008).

Renovation to make houses customised to residents now accounts for more than half of the construction market in many developed nations. To improve the capacity of residential buildings to adapt to changes in space, the responsiveness of buildings to end users should be improved, while at the same time increasing efficiency, sustainability, and capacity for change (Kendall and

Teicher 2000). Eric von Hippel explains that user participation in design is desirable to manufacturers as well as residents, pointing out that "a variety of manufacturers have found it profitable to shift the tasks of custom product design to their customers along with the appropriate toolkits for innovation" (von Hippel 2005).

Infill components of residential building could be a significant constituent of the toolkit for user-driven house customisation. The infill components employed in this paper is *Movable Lightweight Partition Components* developed by Korea Institute of Construction Technology. It is mainly comprised of panel type wall components, storage type wall components, door components, and accessory components, having features as described in Figure 1.

Overview	Purpose	Partitioning rooms inside of unit : bedroom, living room..
	Type	Components : prefabrication, minimizing on-site work
		Dry process : fabrication without using water
	Scope	Structurally self-reliable, having the following features
Features	Easy Construction	Light and easy for two people to fabricate and separate
	Movability	Detachable – easy fabrication and separation
	Easy Remodeling	No impact to support or structure when separating
	Sound Insulation	Standard of *Architectural Institute of Japan* passed
	Shock Resistance	Impact test passed
	Reusability	Componentization
	Easy Wiring	Panelizing of Wiring*

* Electric wiring and piping is out of scope of this research

Figure 1. Overview of movable lightweight partition wall components (KICT 2007).

Coordinating and locating components before fabrication has always being one of the most challenging tasks encountered in modular construction process (Tatum and Korman 2000, Korman 2001, Lu and Korman 2010). That is because historically a specified model for plan design and fabrication with module components did not exist. Situation gets more challenging in renovation of modular houses and even more when an end-user tries to drive the process. That is, despite of development of infill components and interface, residents in need of home renovation with components currently have little information available on how to rearrange and fabricate the components based on the design changes, which component can be reused for their new house layout, and how to minimise additional purchase of components.

One of the most convincing reasons for the difficulty is that few studies have been done on a means of supporting modular construction in early stage of design. When users, therefore, want to remodel their home built with module components and to have it fabricated, they experience the major limitation of current computer-aided design tools, which results in frequent interruption in remodelling process because of lack of information about reusable components. In order to make improvement, required features of 3D architectural design tools for modular construction needs to be completely redefined, and the tools should be improved with due regard to component reusability.

3. Approach

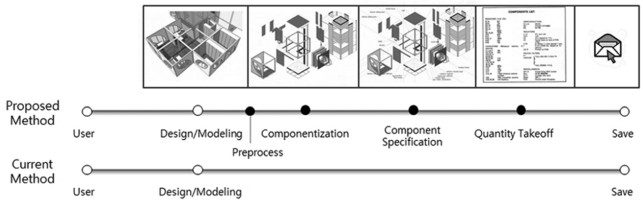

Figure 2. Research approach.

This study proposes a different approach to build user-centric environment for design and fabrication of house with module components. While the current web-based solutions in practice such as *Autodesk Homestyler* and *Sweet Home 3D* provide only visualisation function to support communication on design idea, the proposed method in this study defines the absence of a single, specialised platform that provides fabrication information extracted from design model as the reason why users have difficulty in making design change in their home built with module components. Particularly, this research focused on help to reuse module component in design changes. We developed a system that helps to componentise apartment unit layout into housing module components to give component documentation and quantity take-off based on component reusability to residents interactively based on the design changes that they make.

The methodology comprised the following four phases: preprocess, componentisation, component specification, and quantity takeoff phases, which correspond to Sections 4.2.1 through 4.2.4 of this paper. The flow diagram of the proposed method is represented in Figure 3. A detailed description of the procedures involved in each methodological phase is provided from Section 4.2.1 to 4.2.4. Electrical wiring and piping system is not within the scope of this research.

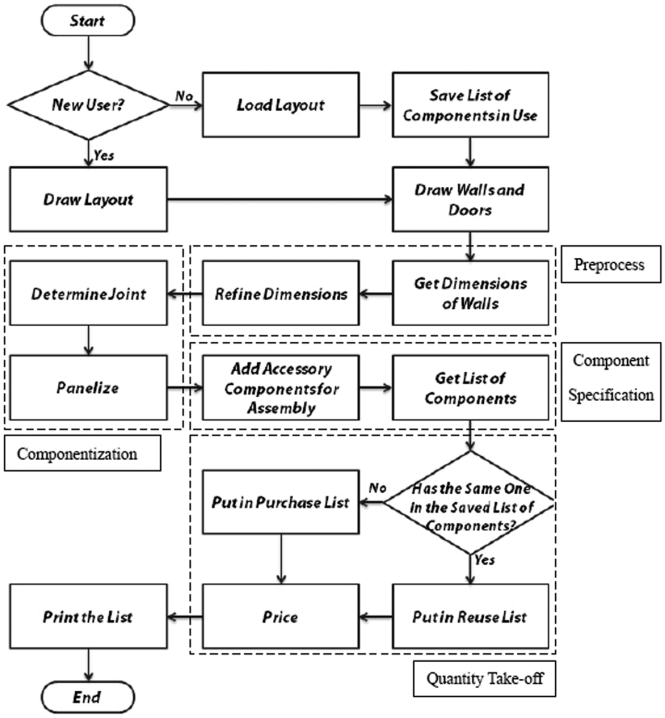

Figure 3. Flow diagram of the proposed method.

4. System design

4.1. SOFTWARE ENVIRONMENT

In this paper, *Sweet Home 3D*, an open-source free interior design application with 2D and 3D preview was used as a parent system. *Sweet Home 3D* enables users to easily draw their housing layout, which allows them to make the changes in design and to have it visualised with ease. It is written in Java and offers the ability to extend the functionalities of this application (Chong et al. 2009).

In this paper, we used this software with the rules to componentise home design layouts based on the components in hand. This rule-based housing design system offers the users a promising application for housing remodelling because it allows times and efforts to be saved from calculating the required components based on reuse.

4.2. SYSTEM DESIGN

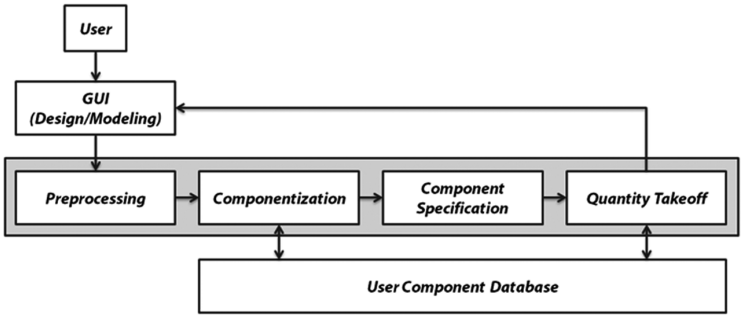

Figure 4. System architecture.

4.2.1. Preprocess

In this phase, information given in schematic layout is collected and refined into the required format for the following phases. This phase is comprised of three sequential steps.

Step 1: Extracting Component Information The first step of preprocess phase is to extract component information. Every component has name, location and dimension attribute. In particular, each wall component has its own values for identity number, location of both ending points, and the distance between the two points. The ending points are measured at the centre line of the interior walls, while those of any panel type walls which encounter exterior wall, columns, doors or storage are measured at the dividing line.

Step 2: Correcting Wall Type Once component information is extracted, some of wall components which adjoin a storage component undergo change in its value. This step is necessary because storage components serve as a kind of wall component in the actual construction stage, while end-users of the system put storage components to the schematic layout as furniture. That is, panel-type wall component is not necessary in where it adjoins storage component.

Step 3: Getting Wall Dimensions Refined This step decides whether the dimension of the components is inside dimension, and if not, changes it into inside dimension. When one of the ending points of a component is the same as one of another, it needs to be refined in the required format, inside dimension, for the next phase. As the ending points are measured at the centre line of the interior walls, half of the thickness of the wall should be subtracted from the original distance to get inside dimension.

4.2.2. Componentisation

The Componentisation phase divides the drawn walls in line into wall components based on the type of combination among walls such as I, L, T, and cross type. This phase is comprised of two sequential steps.

Step 1: Determining Joint This step determines the type of combination of each wall among I, L, T, and cross type, and adds the joint information to the dimension value. I type wall does not meet other interior walls and it is determined when it does not share either ending point with other walls; L type wall meets another wall, and it can be decided when two walls share one ending point; T type wall meets other two walls, and it is determined when the three walls share one ending point; cross type wall meets other three walls, and it is determined when the four walls share one ending point.

Step 2: Panelising Panelising divides the walls drawn in line by the user into panel type wall components. The standard size of the module used in this study is 300 mm, 600 mm, and 900 mm. As walls are not always divisible by modules, irregular panel which is as long as the remainder could be required. The goal of this step is to minimise the amount of irregular panels while panelising the walls. Irregular panel size ranges from 100 mm to 400 mm.

4.2.3. Component specification

The component specification phase determines what accessory components are necessary in order to fabricate the design in practice. This phase is important because the 3D models made by the user is originally do not have any information about fabrication such as what else components are needed to combine the wall modules.

4.2.4. Quantity takeoff based on component reusability

The quantity takeoff phase decides whether the user can reuse components currently in hand for the required components to fabricate the new design. This phase refers to user component database and makes a list of reusable components and need-to-purchase components. Once the list is completed, the system prices the components and prints the result.

After the four phases of the system, the information extracted from the schematic layout finally results in the useful information, the list of the required components for the layout. The list is printed, being categorised into reusable one and need-to-purchase one.

4.3. USE SCENARIO

A user has a house built of module wall partition components developed by Korea Institute of Construction Technology. The user wants to make changes in the current layout of the house and remodel it. The user uses the system proposed in this study to visualise his or her new design idea and get information on how the modules should be fabricated, what else modules he or she need to buy.

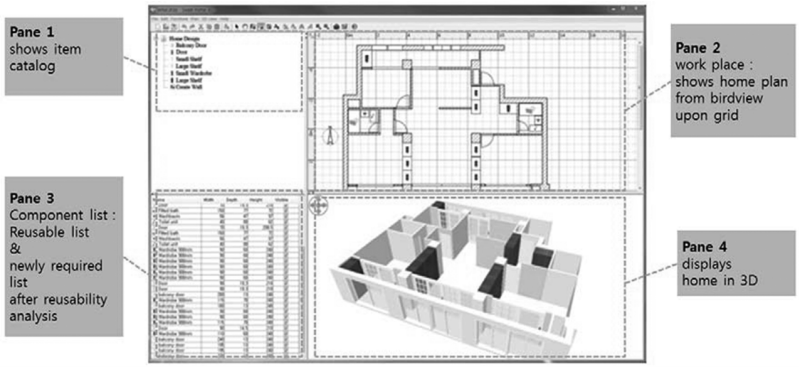

Figure 5. Interface of the proposed system.

4.4. CASE STUDY

The two layouts of one house renewal case were designed based on a single story unit in Figure 6.

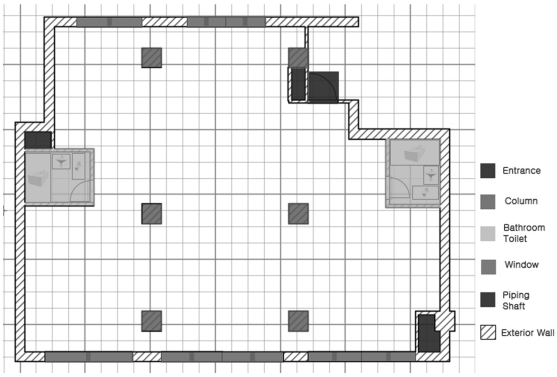

Figure 6. Physical constraints.

All outer walls are 300 mm thick and the physical constraints include configuration of outer walls and location of columns, the front door, and windows. The

location of two bathrooms was fixed in this study because bathroom system is out of the scope of this study.

Figure 7 shows the two plans and the corresponding 3D digital models. One is the pre-remodelling plan and the other is the post-remodelling plan. For example, the layout on the left column of Figure 7 is changed to the other as a result of unit remodelling.

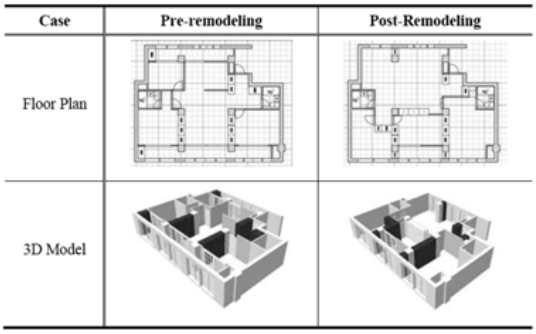

Figure 7. The initial layout and the one after remodelling.

TABLE 1. Required components.

Type of Components			Size (mm) W, H, D	Reuse Amount	Purchase Amount
Partition Wall	Panel Type	Regular	300 × 2400 × 100	1	0
			600 × 2400 × 100	2	0
			900 × 2400 × 100	5	0
		Irregular	100 × 2400 × 100	1	0
	Storage Type		600 × 2400 × 600	4/0	0/1
			900 × 2400 × 600	8/0	0/3
	Accessory (Lumber)	Rectangular	20 × 20 × 20	5	0
		Corner	100 × 2400 × 100	0	0
Door System	Door		900 × 2100 × 100	3	0
	Panel		900 × 300 × 100	3	0
	Balcony		2000 × 2400 × 100	1	0

Table 1 presents the results of operation of the system about the case, showing the bill of materials for the remodelling cases, categorising them into two groups, namely Reuse and Purchase. According to the result of quantity takeoff based on the material reusability, the user needs to purchase the components on the first column from right side of Table 1, and the other required components can be reused among ones that the user already have.

5. Discussion

The application of the strategies described here may reduce human efforts in complicated process of re-arranging components according to new layout design and help to increase the use of module components in practice.

One of the best contributions of this study is to define the functional specification of digital design system especially for modular construction. As the existing systems focus on wet construction and offers helpful functions usually for it, digital design system framework for modular construction has not existed, nor does the definition of required functions exist. In the future, extended study dealing with location-based quantities and movement of electric wiring and wet place would make the system more useful.

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CONSTRUCTING COMPUTATIONAL ASSOCIATIONS BETWEEN ORNAMENTAL DESIGNS

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Abstract. This paper presents the application of a computational model of association to the domain of real-world ornamental designs. The driving principle of the model, interpretation-driven association, is discussed with respect to its suitability to design applications. An implementation of the model is presented, in which associations are constructed based on topological and typological relationships within each design's structure, rather than based on literal similarities. Results are presented which demonstrate that the implementation and the model from which it was derived are capable of associating between real-world design objects.

Keywords. Design association; design interpretation; computational modelling; ornamental designs.

1. Computational association in design

Association, in this paper, refers to the process of constructing new relationships between different ideas, objects or situations. This is a similar definition to that of computational analogy-making (French 2002), but without the requirement that the relationship so constructed be then used to transfer knowledge between the domains of the two analogues. Association can be considered a foundational component of analogy-making, which is considered an important cognitive process in designing (Qian and Gero 1996).

In a design context the representations of the objects to be associated will change before, during and after the association is made. In this way design is unlike many problem-solving domains to which computational models of association have been applied. Designers modify their representations of both the design problem and the emerging design solution while they are designing. They act to further the design, reflect on that action, and act again (Schön 1983). These representational modifications are not necessarily gradual or incremental, they are often deliberate reinterpretations that construct new design situations (Gero 1998).

An important question in the computational modelling of association is how to re-represent and transform the representations of objects in such a way as to enable the construction of new associations (Kokinov 1998). Re-representation in association research is complicated by a recursive question: How can the representation that enables a new mapping be constructed before the mapping itself? And how can a mapping be constructed before the relationship that enables it? These questions parallel those raised in the computational modelling of design. This research approaches these problems by using iterative and parallel processes of transformation and search to construct new representations and associations.

The model of association described in Grace et al. (2011) is well suited to the representational dynamism of design contexts, as it does not require an extensive knowledge base about the domain(s) it is associating. Additionally, the representations used in this model need not possess identical relational lexicons, as associations are found based on similar structures of relationships rather than identically labelled representations. These characteristics arise from the notion of interpretation-driven search. This paper describes an implementation of that model and presents its output.

2. Interpretation-driven association

Grace et al. (2011) define an interpretation as a transformation applied to a representation of an object. These interpretations change the structure and/or content of the representations to which they are applied. This in turn changes the relationships that can be constructed from them. An interpretation-driven approach to computational association involves an iterative, parallel interaction between reinterpretation of object representations and searching those representations for mappings. In this framework, Figure 1, potential interpretations are constructed from the search for mappings, based on what transformations could enable new mappings. Additionally, the search for mappings is affected by what interpretations have been applied to the objects, as each transformation changes the search space. This iterative feedback between searching and

transforming parallels the notion of reflection-in-action described by Schön (1983) as central to design thinking.

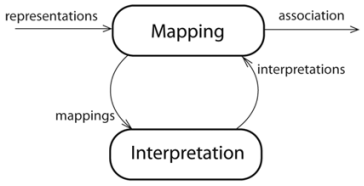

Figure 1. The interpretation-driven framework for computational association.

Models of association-based processes propose that associated objects share patterns of relationships, but not necessarily the attributes connected by those relationships (Gentner 1983). The model used in this research extends this principle to an additional level of abstraction, positing that associated objects need not share patterns of identically labelled relationships, only that the structure of those patterns be similar. The system constructs an interpretation of the objects in which similar structures of disparate relationships can be viewed as alike. This is the basis of the interpretation-driven model of association detailed in Grace et al. (2011) of which an implementation is described in this paper.

The implementation described in this paper will be first assessed for its compliance with the principles of the interpretation-driven approach to association. In order to be judged a complete implementation of the model, the implementation must construct interpretations during the search for mappings, apply those interpretations to affect the trajectory of the search for mappings, and produce associations between interpreted representations. Once it has been demonstrated that the implementation exhibits these behaviours, it will be possible to demonstrate the effectiveness of the model through the results produced by the implementation.

3. Implementation

The computational model of interpretation-driven association was implemented in the domain of ornamental visual designs. This domain permitted the use of vector-based line drawings for which representation construction processes could be efficiently developed. This implementation and the experiments performed using it serve as a proof of concept of the capabilities of the model.

The model begins with the process of representation construction, in which features are extracted from low-level visual representations and organised into

conceptual categories. Relationships between these features and concepts are automatically constructed, and then a graph representation is constructed from these features and relationships. These graphs provide the representations that can be iteratively transformed and searched.

The implementation of the model developed in this research begins with vector representations of ornamental designs and constructs a set of minimal closed shapes from them. These shapes became the features used in the system, each of which was described by the contours of its outline. Outline descriptions are produced by casting rays from the polygon centroid and measuring the distances to their intersection with the polygon's edge. This is similar to the centroid-radii method proposed by Tan et al. (2003). Five example features and their descriptions can be seen in Figure 2. Features were then placed into concepts using a clustering algorithm.

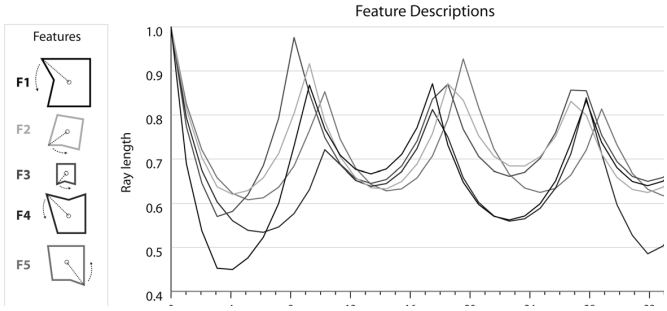

Figure 2. Five example features (on left) produced by the implementation of our model of association. A plot of their descriptions (on right) shows the outlines produced, with the y axis as the normalised side length and the x axis as the point on the outline.

The relationship formation process searched the feature representations for a wide variety of both topological and typological relationships, including relative scale, relative position, relative orientation, same concept and similar concept. These relationships were then converted into graph edge labels, categorising continuous-valued representations where necessary. The resulting graph representations were then used by the system to construct associations in the manner described by the model.

The mapping search process was implemented using a genetic algorithm-based approximation of subgraph isomorphism. The genotype for each individual mapping candidate was which features in one object would be mapped to which features in the other object. The fitness function was then based on the size of the largest contiguous subgraph of identically labelled edges that each mapping produced.

Interpretation in this implementation involved the substitution of edge labels. When an interpretation was applied the edges in one object's graph with a particular label, along with the edges in the other object's graph with a different label were replaced with a third, unique label. This represented the idea that those two relationships were considered equivalent in the context of the interpretation. These interpretations transformed the fitness function being used by the genetic algorithm during the search, affecting the search trajectory as required to satisfy the description of the model.

4. Experiments in association with designs

In order to demonstrate the capability of the implementation – and accordingly the model – to produce associations between designs, a large number of ornamental design objects were given as input and the results were investigated. A subset of those results is presented here.

The six designs with which the association-construction behaviours of the implementation are to be demonstrated are shown in Figure 3. These design objects were gathered from a variety of sources, shown in Table 1.

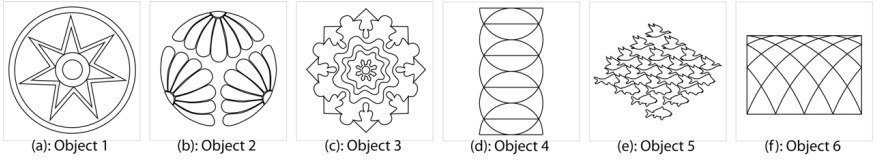

Figure 3. The six designs that are used in associations constructed by our implementation. These vector image representations were manually constructed from source images.

TABLE 1. Sources for the six designs shown in Figure 3.

Obj.	Description	Source
1	Hittite sun symbol.	Humbert (1970)
2	Japanese floral symbol.	Humbert (1970)
3	French empire motif.	Humbert (1970)
4	Ironwork pattern for a gate, fence or balcony.	Cottingham (1824) via Cliff (1998)
5	'Sky and Water I', oil painting.	Escher (1938)
6	Ironwork pattern for a gate, fence or balcony.	Cottingham (1824) via Cliff (1998)

From these six objects three trials were performed, with each trial consisting of constructing associations between two objects. The trials are as follows:

- *Trial 1* associates Object 1 and Object 2.
- *Trial 2* associates Object 3 and Object 4.
- *Trial 3* associates Object 5 and Object 6.

Multiple associations were constructed in each trial as the system can produce different output depending on its historical context – see Grace et al. (2011) for details. Each trial was repeated until 10 consecutive associations were constructed that had already been produced. All unique mappings were recorded, along with the interpretations under which they were constructed. A selection of the results from each trial is presented here.

5. Results

The results images presented in this section use the following formatting:

- Each of the two objects is bounded by a light grey box.
- The outlines of unmapped object features are drawn in grey stroke.
- The outlines of mapped object features are drawn in a black stroke.
- Thin black lines between the two objects join mapped features.
- Thick dashed lines between features of an object show the relationships on which the mapping was based. These mappings are labelled with their respective relationships.
- The interpretation used to construct the association, referred to as *i* in the model, is shown in a box below the two objects.

5.1. RESULTS OF TRIAL 1: OBJECTS 1 AND 2

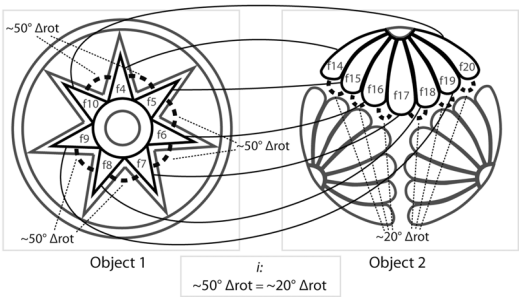

Figure 4. A result from Trial 1 showing an association between Objects 1 and 2. The seven points in the star on the left have been mapped to seven petals in a floret on the right.

Figure 4 shows one of the associations constructed by the implementation during Trial 1. The star-shaped pattern central to Object 1 has been mapped to one of the three florets in Object 2. This mapping was enabled by an interpretation that equates the difference in orientation between adjacent triangles in Object 1 with the difference in orientation between adjacent petals in Object 2. Specifically this interpretation situationally equates a 50° difference with a 20° difference. These relationships are treated as interchangeable while the interpretation is applied, enabling the association.

5.2. RESULTS OF TRIAL 2: OBJECTS 3 AND 4

Figure 5 shows one association constructed by the implementation during Trial 2. The eight arrow-headed objects surrounding the perimeter of Object 3 have been mapped to the eight circular segments in the centre of Object 4. This mapping was enabled by an interpretation that equates the difference in orientation between adjacent arrow-features with the difference in horizontal position between the segments. Unlike the interpretation used in Figure 3 this interpretation is heterogeneous with respect to relationship type.

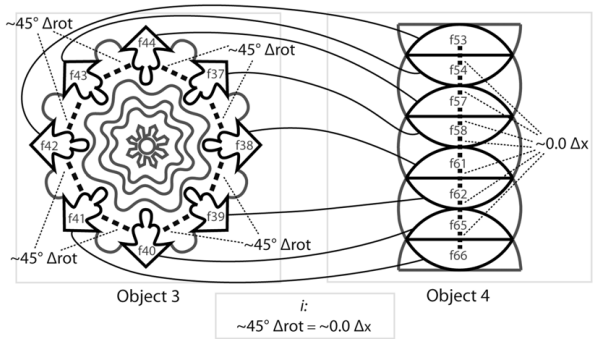

Figure 5. A result from Trial 2 showing an association between Objects 3 and 4. The eight features surrounding the design on the left have been mapped to the eight segments in the design on the right.

Figure 6 shows a different association that was constructed by the system during Trial 2, this time connecting the six concentric shapes that form the body of Object 3 with the six curve-sided triangles that adjoin the centre of Object 4. This mapping interprets a set of "contains" relationships in Object 3 – relationships based on one feature being entirely inside another – to be like a set of orientation difference relationships in Object 4. These two sets of very different relationships share a common structure and were able to be associated through interpretation by our implementation.

5.3. RESULTS OF TRIAL 3: OBJECTS 5 AND 6

Figure 7 shows one of the two associations constructed by the system during Trial 3, in which the four rows of fish-shaped features, thirteen in total, are mapped to the four rows of four-sided shapes, also thirteen in total. The other association that was constructed in this trial had the same overall structure but mapped the triangular structure of the fence in Object 6 to the birds in the upper half of Object 5 instead of the fish. This association demonstrates that

visually complex patterns can be represented as graph structures with simple underlying structural commonalities. Associations can then be constructed based on those commonalities using interpretation-driven search.

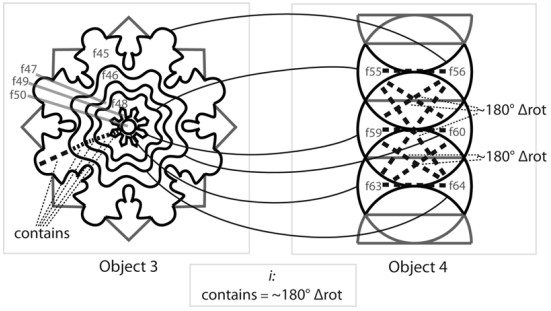

Figure 6. A result from Trial 2 showing an association between Objects 3 and 4. The six concentric shapes in the design on the left have been mapped to the six three-sided curved objects in the design on the right.

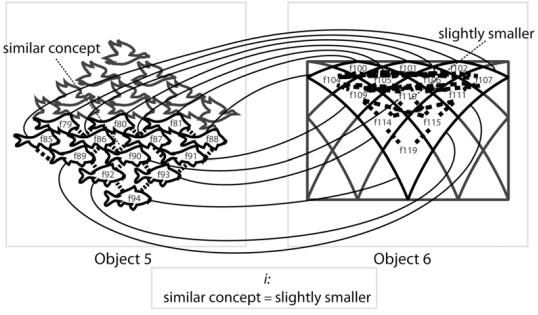

Figure 7. A result from Trial 3 showing an association between Objects 5 and 6. The rows of gradually more abstract fish on the left have been mapped to the rows of gradually smaller quasi-rectilinear shapes on the right.

6. Discussion

The challenge of applying computational association to design tasks is that the act of designing possesses qualities that differ significantly from the well-structured problem-solving domains to which computational associative reasoning is typically applied. Design is a sequence of situated acts (Gero 1998) that is characterised by iterative cycles of reflection and action (Schön 1983) and intended to solve a wicked problem (Rittel 1988). The model described in Grace et al. (2011) can be shown to address each of these characteristics, and the implementation described in this paper demonstrates the feasibility of that model. This approach to computational association is both possible and

demonstrably suited to design, which will enable a furtherance of association in design research.

The model incorporates the effects of experience on both object representation and interpretation construction, making these processes dependent on the historical context of the system performing them. This is a significant step towards the modelling of association in design as a situated process. The associations shown in Figures 4 through 7 are the product of a system for which the output is dependent not only on the current inputs but also on what has come before. If the system has successfully used a particular kind of interpretation on a past association problem it can attempt to re-use it again, leading to 'priming' effects of past input on results.

The interpretation process that enabled all of the results presented in this paper involves the iterative construction of potential mappings, the investigation of those mappings for avenues for interpretation, and the generation of interpretations that transform those mappings. This process is an analogue of the reflection-in-action process described by Schön (1983), in which the critical role of the seeing-as process is performed by interpretation. In formulating association as being based on this iterative, reflective approach, the model described in Grace et al. (2011) renders the association process more compatible with design thinking.

The classification of design, particularly creative design, as a wicked problem prohibits the specification of a complete solution space before or during the design process. This means that the space of possible designs can change – often dramatically – during design itself, and that any computational model to be applied to design must be capable of operating in an environment of representational dynamism. The results presented in this paper were generated using representations that were developed by the system during operation. These graph representations of object features and the typological and topological relationships between those features were constructed from low-level visual input by the system itself. These representations were then transformed by constructed interpretations.

The development of a computational model of association that is demonstrably suitable for application in design opens up opportunities for future research. With the incorporation of a knowledge transfer process, the model could be used to construct analogies. Computational analogy-making can be used in design for proposing or modifying candidate design solutions, although Goel (1997) suggests it could also be used for elaboration, decomposition and problem-framing tasks.

The process of association could also be used as the basis for a computational model of design style. The factors that influence design style do not typi-

cally lead to style descriptions that can be simply delineated in most computational design representations (Jupp and Gero 2006). Association has been used to judge similarity by mapping what features of two objects are similar and what features are different but structurally comparable. This is referred to as 'alignable difference' and has been found to strongly predict human similarity judgements (Markman and Gentner 2005). An interpretation-driven approach could use the interpretations on which associative similarity judgements were based to characterise how objects were related. These characterisations of the kind of transformations necessary to relate two objects could form a description of design styles.

The results presented in this paper serve as a proof-of-concept of the interpretation-driven search framework for computational association in design. It has been demonstrated that the model presented in Grace et al. (2011) can be used to produce interesting associations between representations of real-world design objects that it has constructed.

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ASSOCIATIVE PARAMETRIC DESIGN AND FINANCIAL OPTIMISATION – CASH BACK 1.0

Parametric design for visualising and optimising return on investment for early stage design decision-making

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Abstract. Cash-Back 1.0 presents research on the development of methodologies and technologies to simulate the cause and effect of early stage geometric design alternatives of buildings and the real time results upon financial pro-forma. Through the encoding of design rules and their associative relationships to financial pro-forma the research illustrates enhanced visualization of early stage building design decisions and their cumulative impact on financial goals and constraints. The research presents value an associative parametric design process affords often-disparate domains through correlation and visualization. The paper describes incorporation of a feedback loop between pro-forma and geometric models in conjunction with an optimization method. Given the level of uncertainty in early stage design decision making the research contributes partial solutions to the domain problems of design decision uncertainty and design cycle latency and is further argumentation for increased use of parametric design methods and automation to support design domain integration.

Keywords. Parametric design; genetic algorithm; design decision support; multi domain optimization; domain integration.

1. Introduction

Architecture, engineering, construction professionals and owners need to define objectives, propose and iterate on options, analyze these options with

respect to the pre-defined goals, and make decisions conventionally with high degrees of uncertainty in early phases. Early stage design decision making is often based on tacit rules of thumb and reflection (Schön 1983), and although given the opportunity to correlate competing objectives, they are rarely visualized and understood as parameter coupling problems (Hirschi and Frey 2002). Design uncertainties are exacerbated by large gaps in the correlation of each of these domain experts' goals; the linking of project geometry to financial drivers and objectives is our case in point. These gaps in part exist as a result of differing tool sets, differing problem definition, differing representation and abstraction methods (Mitchell 1990), and differing ability to visually and analytically communicate the cause and effect of their specific design domain decisions for a project alternative (Akin 2002). Design is by definition an ill-defined problem computationally as there are multiple solutions typically as a result of multiple objectives (Simon 1973). Adding to this complexity, design is a social and technical process where there is a need to coordinate poorly linked processes and data amongst a wide range of team members and stakeholders (Fischer 2006). This lack of linking and correlation is in fact where the research starts.

The research here presents a prototyped enhancement for early stage design and domain integration which is produced in terms of rapid generation of design alternatives that are visualized, qualified and quantified across multiple objectives, design and financial, leading to a higher fidelity understanding of a project's simplified return on investment (ROI).

2. Research motivations

The research is motivated by an interest in proving out the value of parametric design as a core methodology for improving upon domain integration, design cycle latency reduction, and further demonstrating the necessity for design automation and integrated optimization. More narrowly we enumerate the research motivations through a set of contemporary deficiencies in traditional design and planning process; 1) deficient rapid design alternative generation; 2) deficient domain integration; 3) deficient visualization of cause and effect; 4) deficient use of sensitivity analysis; and 5) deficient understanding of the complexity inherent in parameter coupling problems. Building designs are based on multiple participants, multiple objectives and attributes which include, but are not limited to, technical, financial, aesthetic, environmental and functional aspects (Smith and Jaggar 2007). The decisions made during the early design stage in relation to these attributes affects the real value of the project (Jaggar 2002). Leveraging design optimization and domain integration approaches in the early phases offer the greatest influence upon a

project's costs and for minimizing expenditures associated with the design (Bon 1989). Research of current industry practices indicate a propensity to rush the design and planning stage forfeiting the benefits of paying attention to cost estimation (Smith and Jaggar 2007) arising from the lack of integrating such requirements into the design process (Akin et al. 1998). Furthermore the lack of correlating development economics and objectives into the design process has been under-developed and explored (Ferry et al. 1999, Wong et al. 2005). Architects somewhat uniquely prefer to contemplate more design alternatives than other professionals while searching for a design solution (Akin 2002). Parametric design tools allow designers to generate more design options more rapidly (Aish 1992, Burry and Murray 1997, Gerber 2009). However in doing so the design team also must evaluate performance criteria for each design solution in terms of requirement and constraint satisfaction. Rapid generation of design alternatives coupled with rapid analysis allows designers to minimize the design cycle and improves the quality of the end product (Yi and Malkawi 2009) however this has yet to become the normal practice in the early stage modeling of a financial pro-forma in concert with programming and massing design studies. The absence of automatic integration of discipline specific information is costing AEC professionals valuable time (Flager et al. 2009). The research demonstrates an improvement upon the current level of domain integration, in particular the developers' pro-forma with the concept and massing program models of the architect. The integration of multiple domains leads to the problem of multi-dimensional or multi objective optimization. As with all 'ill defined' design problems optimality is a trade off. However through integration a design team can better reduce uncertainty and understand the trade-offs through a correlated visualization and empirical quantification of these trade offs (Gerber and Flager 2011). Another deficiency is of visual clarity of the project's constraints and their impact on geometry and financial models. While current modes of development practice—'go no go' decisions on projects—rely on rules of thumb and quick calculations owner developers are not being given the opportunity to see visualized optimality in terms of overall massing, site coverage, and programmatic mix; geometry and its cause and effect on ROI. A further deficiency is of a design team's ability to understand cause and effect with sensitivity. Sensitivity analysis provides designers a tool to measure the relationships between the multiple domain objectives (Saltelli et al. 2000). While it is widely understood that structural costs and geometric differentiation will have large effect upon project financials, it is not part of current design practice to visualize a sensitivity analysis that can be quantified through generation of many design alternatives. Crucial for multidisciplinary design optimization is the ability

to identify the weighting of design trade-offs, what-ifs and their impacts on the different disciplines (Hardee et al. 1999). Coupling among design tasks is an important measurement of the complexity which in turn severely affects the design cycle completion time and design solution quality (Hirschi and Frey 2002). Design complexity increases rapidly when the interdependencies between design elements, or number of parametric relationships grow (Erhan et al. 2010). Fundamentally the human designer's inability to manage a large number of coupled parameters inherent in a multi-domain problem such as the optimal programmatic and massing and financial model of a building supports the argument for increasing the formalization of parametric process and the use of automation techniques for linked domains.

3. Precedent solutions and background research

Associative parametric design methods and tools have been used as an answer to many deficiencies listed above (Mitchell 1990, Burry and Murray 1997, Motta 1999, Aish and Woodbury 2005, Kilian 2006, Gerber 2009) including for; form generation and structural optimization of a high-rise tower considering cost and value relationships (Chok and Donofrio 2010); rapid design and structural geometry alternative generation (Rolvink et al. 2010); improving collaboration of design team linking with other design disciplines (Hladik and Lewis 2010); and for sharing domain knowledge by providing rapid design performance feedback (Shea et al. 2005, Holzer et al. 2007, Flager et al. 2009) for examples. Another precedent was developed to assist architects with understanding the cost of construction projects in the initial design stages (Jrade and Alkass 2007). Another, ViSA (Visual Sensitivity Analysis) method was proposed to help in decreasing the complexity related to interdependencies between design elements by visualization of sensitivity of parametric design models (Erhan et al. 2010). Furthermore, with the advent of Building Information Modeling (BIM) the software providers have begun to further offer cost estimating features to assist multidisciplinary team an ability to forecast their ROI (Azhar et al. 2008). Building volume optimization (BVO) is suggested in early design stages for finding cost efficient building-volume designs by pointing out the dependencies between geometry and cost (Schoch et al. 2011). However, there still remains a gap in tool and method development to specifically more tightly couple the developer's financial modeling and objectives to that of early stage design modeling.

The research method used for the development of the prototype tool named 'Cash Back 1.0' is based on three primary activities: problem formulation, process integration, and design exploration and optimization. The first step is to formally define the design problem including the design objective, vari-

ables and constraints. The design objective of the research is to visualize and optimize return on investment ROI. The constraints are the criteria—bounding box for example—that a design option must satisfy to be considered feasible. Finally, the variables are the parameters—program mix for example—of the design that can be manipulated within defined ranges to achieve the objectives and satisfy the constraints from which we build an associative parametric digital model. The second step and goal of the process integration activity is to link the design model to the financial model in the form of excel tables and then to the automation and optimization mechanism. Next, the data flow between the tools is automated to reduce design cycle latency that is pervasive in current design practice. Once the design problem is formalized and an integrated process model has been created, the designer can then design explore (Kilian 2006). However, exploring the design space using manual trial and error methods is still impractical due to the large number of possible alternatives. In this case, an optimization technique using a genetic algorithm is applied to systematically breed, evaluate and rank the design space in an automated fashion. By generating plots of the alternatives along constraint ranges, trade offs and competing parameters can be discerned and decided upon.

4. Tool design

'Cash Back 1.0' was designed through use of Rhino, Grasshopper, Galapagos, and Excel. The tool was conceived of as a prototype with placeholders and variables for future incorporating of additional constraints and pro forma requirements. The Grasshopper algorithm definition is divided into 8 parts named according to their functions:

1. *Site constraints*: defines the allowable dimensions of the site including the boundaries, setbacks, and maximum allowable building height, which derive a bounding box for maximum geometric envelope. All parameters in this part are constant throughout the entire optimization process, and defined by the designer.
2. *Program ratio*: divides program into 3 varying ratios of retail, office and residential areas; the sum of all ratios should not exceed 1.
3. *Program geometry*: defines the length and width of each program's base, and height portion of the building that accommodates it. This parameter is used as a genome (variable) for the Galapagos optimization process, through the generation of massing configurations of each program.
4. *Continuous geometry*: defines the upper surface plane of each program mass from which the next mass is parented and generated. This part of the algorithm is necessary to ensure that the upper mass length and width change as a variable, and are dependent on the upper surface dimensions of the mass below; whenever the lower mass changes, the upper mass automatically optimizes

itself to accommodate changes, maintaining an overall programs ratio of 1.

5. *Cost and revenue*: defines a series of simplified mathematical functions for cost and revenue calculation based on varying surface floor areas and number of floors. This component is structured to be extensible and to accommodate real world cost complexity.
6. *Profit calculation*: defines a series of simplified mathematical functions of the concept of net profit calculations, through subtracting total cost from total revenue.

   Floor surface area × no. of floors = overall program surface area
   Selling price per sq. ft. × program overall area = total revenue
   Cost per sq. ft. × program overall area = total cost
   Total revenue – total cost = estimated profit (fitness value)
   This component is structured to be extensible and to accommodate real world profit calculation methods such as net present value and internal rate of return equations.
7. *Galapagos*: is an evolutionary algorithm component that, in our case study, works off independently driven parameters and is based on one calculated fitness value. The single-numerical fitness value is defined as the subtraction of two hypothetical calculated market values: overall construction costs and total sales revenue, with profit maximization as Galapagos' optimization objective (Rutten 2010).
8. *Excel exporter*: defines an excel exporter that has been incorporated into the algorithm to export the values of floor plate areas, heights, and dimensions to the developers' excel spreadsheet for their further use and investigation.

4.1. CONTROL GENES AND FITNESS VALUE

The genetic algorithm component, Galapagos, breeds designs though generations and offspring by altering the parameters i.e. control gene values. These genes include (Figure 1):

9. *Residential Program ratio:* one ratio composed of three values, each defining the number of floors of each program, whose sum is equal to 1. Within this context, only the residential value is altered by Galapagos. The other two values are determined by changing the parameters mentioned below.
10. *Base length of one side of the volume (side X or Y):* changes the length of one of the sides of the program mass. The other side is determined by altering overall floor plate area.
11. *Floor-to-floor height:* altering the height of each floor, which consequently changes the number of floors of each program within the bounding box defined by the constraints.
12. *Program overall area*: changes the overall area of each program which impacts the number of floors and the size of floor plates.

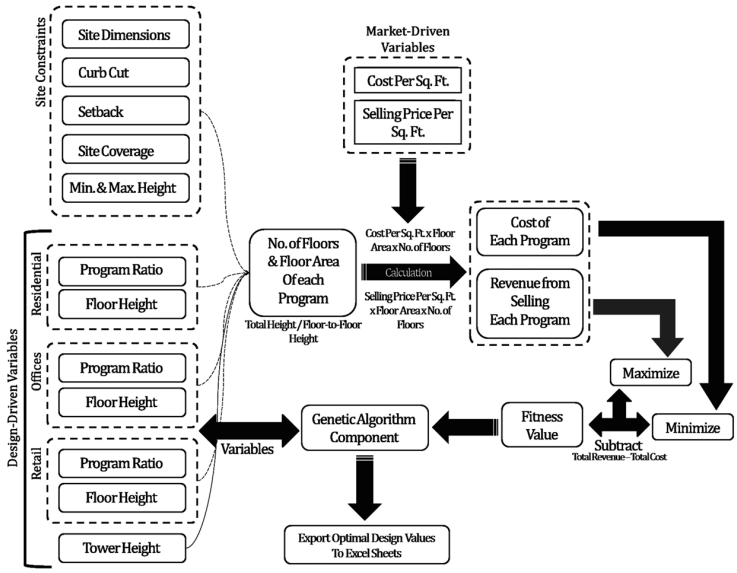

Figure 1. Optimization workflow showing the design-driven and market-driven variables as well as the sequence of optimizing the form.

While the control genes are independently driven numerical sliders, the fitness value is a dependent number calculated using a series of simplified mathematical functions that operate based on the control genes, and site and program constraints and requirements. In this working context, the series of generations were generated from an initial genome (parent) with the following parameter values:

Residential program ratio = 0.60
Floor-to-floor height: Retail 4.50 m, Office 4.20 m and Residential 3.5 m
Base length of one side: Retail 102 m, Office 65 m and Residential 132 m
Total Program Area: 400,000 m²

These values represent a basic scenario of a mixed-use tower for experimental purposes where optimizing programmatic mix for profitability is the driving fitness criteria. Within this framework, Galapagos breeds the fittest genomes a product of parent and mutation factors to populate another generation, and so on. This process results in eliminating parameters that performs worst and breeding parameters that are most fit until Galapagos hones in on a generation with the most-fit offspring. In our case study, the selected offspring showing the highest hypothetical profit value is a tower with overall residential volume of 280,000 m³, offices area of 430,000 m³, and retail area of 1,900,000 m³.

5. Results and analysis

With the linking of the four components; the parametric model, the automation algorithm, the spreadsheet and the genetic optimization algorithm, the designer is able to more efficiently integrate into a project workflow the ability to rapidly design optioneer with return on investment (ROI) incorporated a-priori. 'Cash-Back 1.0' offers a way to efficiently create a parametric model with capabilities to calculate and visualize (ROI) during the schematic design phase. The system provides for multi-objective optimization of building geometry in search of an optimal programmatic configuration that provides maximum revenue and minimum expenditure associated with the design and construction. For this experimental study, 'Cash-Back 1.0' generated 56 generations. A pareto optimal front is noticeable from the plotting of the data set as the solution space curve flattens and illustrates smaller and smaller variations evidencing of honing in on a program mix and increase in profitability. The optimal solution for our initial experimental mixed-use case can be seen in (Figure 2) Generation 12.

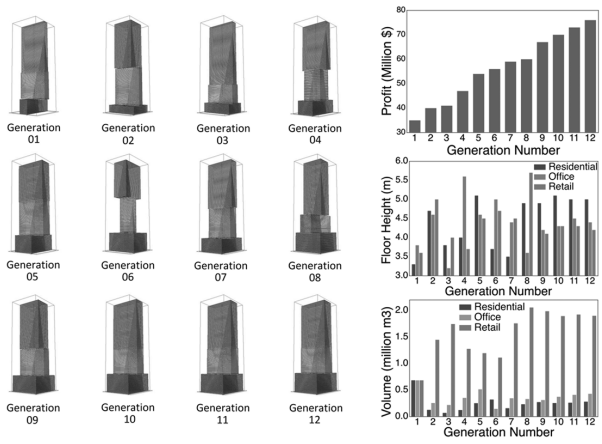

Figure 2. Illustration of a sub-set of single offspring from 12 generations illustrating an optimization of project profitability as functions of design parameters. The hypothetical profit value of our mixed-use building goes from 35 to 76 million seen top right, while Floor Height and Volume values are changed accordingly.

6. Conclusion

The paper presents a prototype that integrates disparate design models from different expert domains, their often differing and competing goals, in order to rapidly communicate trade-offs and maximize project value. The integration minimizes errors based on uncertainty and minimizes latency in the generating

and evaluating of large multi-objective solution spaces (design alternatives). The research builds upon parametric design technology and methods, automation and optimization technologies and methods, and creates a multi-disciplinary design and analyses processes to optimize for project value, here initially and purposefully limited to simplified project financial pro-forma. It presents a partial solution for the problem of deciphering cause and effect where the understanding of the weighting of factors can be near impossible without computation. 'Cash-Back' is being continued through the research and development of more robust implementations on multiple platforms including Gehry Technologies Digital Project tied into a commercial risk analysis package and a custom implementation using Autodesk's Revit and Green Building Studio as an energy use intensity calculator. These tools are being applied to both hypothetical and real world projects to amass a data set to statistically analyze the improvement on the quality of solutions. In conjunction the research looks to continue to develop metrics that look at design process map improvements, design cycle latency for example by virtue of implementing these tools into early stage design decision making.

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TOWARD A PERFORMANCE-ORIENTED ARCHITECTURE

An integrated design approach to a real-time-responsive structure

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Abstract. This paper started from the study of "performance-oriented architecture" for the purpose of developing a real-time-responsive prototype that can enclose large expansive interior space. Questions regarding the relationship between the structural arrangement of systems and the natural environment initiated an investigation in Phyllotaxis. It has been found in plant systems for the optimisation of photosynthesis with harvesting maximum amounts of solar energy. In the design of a real-time-responsive prototype, an algorithmic approach is introduced with the mathematical interpretation of Phyllotaxis and its translation into the global geometry of the prototype. Also, the usage of a Voronoi diagram is parametrically configured to form the local geometry of the prototype. The interactive mechanism of the prototype was achieved with an assorted computational application. Furthermore, with the demonstration of the aforementioned prototype in both digital and physical environments, its implementation process is explained.

Keywords. Performance-oriented architecture; phyllotaxis; Voronoi diagram; real-time-responsive structure.

1. Introduction

The concept of "Performance-oriented Architecture," originally proposed by Michael Hensel, is based on the term 'performativity' in which all elements in both the built and natural environment are heterogeneous and in constant response to one another as well as external stimuli. Hensel (2010) employs the term 'performance' to address the limitations of 'representation' and 'meaning'

in reference to the central issue of post design optimisation (the functional issues that arise toward the later stages of the design process which result in the alteration of initial design intentions). Among the many milestones that were used as a foundation to 'performance-oriented architecture', the themes that are significant to the development of this research are 'performativity' and complex biological systems. In this paper, an integrated approach between botany, specifically Phyllotaxis, and architecture is developed in the process of making a kinetic system that encloses large unencumbered spaces through real time environmental response.

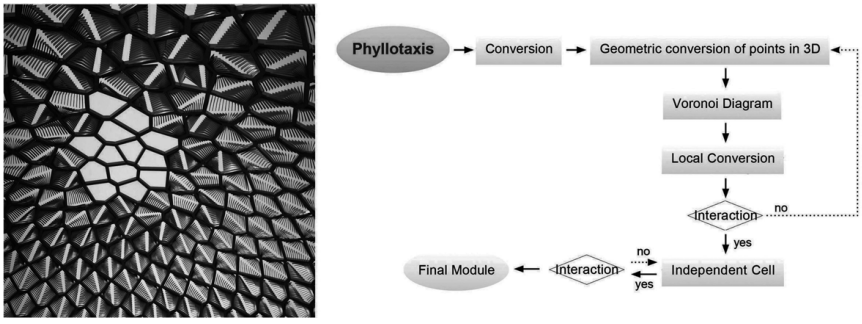

Figure 1. An integrated approach of a real-time-responsive structure.

Phyllotaxis provides architects with the opportunity to achieve maximum uniformity for infinite planar surface areas. The maximum uniformity is employed as a method of optimising the interaction between the prototype and external stimuli in the concept of "performance-oriented architecture." Uniformly arranged points in Phyllotaxis show their potential as the regulating positions to configure a global geometry and the center points of individual cells within the global geometry of the prototype. Here, the individual cell is regarded as a local geometry of the prototype. However, the study of Phyllotaxis was limited to its two-dimensional configuration in theory, so its usage was not fully developed in practice that requires its three-dimensional application. In this paper, the three-dimensional configuration of Phyllotaxis is developed in Rhinoceros 3D and Grasshopper. The boundary condition of each individual cell that has a Phyllotaxis point as its center provides optimised distribution of real time interaction with the stimuli within the proposed responsive prototype. In this paper, a Voronoi diagram was employed for the design of the boundary condition and implemented in Rhinoceros 3D and Grasshopper. The kinetic mechanism of the responsive prototype was tested and developed with the combination of various computational applications including Arduino,

Firefly, Grasshopper and Rhinoceros 3D. Environmental data communication was made seamlessly in real time through the use of photo sensors, motors, and Arduino microcontrollers. Through the combination of these applications, digital and physical environments are fused together to provide real time interaction by elongating the experience of the users and enhancing the spatial quality of the prototype. In this paper, the assorted computer application of the prototype was developed for demonstrating a performance-oriented architecture that responds to the changes in environmental stimuli in real time with the employment of Phyllotaxis and a Voronoi diagram. Furthermore, the physical implementation of an individual kinetic module is inserted in each local configuration of the prototype.

2. Phyllotaxis: configuration of global geometry

Phyllotaxis was first coined by botanist Louis Bravais and explorer Auguste Bravais in 1837. During this time, the development of a two-dimensional optimisation scheme began to turn toward mathematical and systemic rather than observational studies (Adler et al. 1997). These mathematical and systemic studies in the 1830's led to a formula designed by Roger V. Jean, where the common divergence angle (d) in the arrangement of leaves found in plants is related to the Fibonacci sequence (1, 2, 3, 5, 8…) (Jean 1994) as below.

$$d = 360° \left(2 + \left(\frac{\sqrt{5}+1}{2} \right)^{-1} \right)^{-1} \tag{1}$$

The design of the proposed real time interactive structure begins with converting the two-dimensional scheme designed by Jean into an algorithm that serves as the foundation to parametrically determine a globally distributed set of uniform points in three dimensions. The following formulae shows uniform points generated in x, y, and z directions where n is the number of points.

$$F(x) = \cos(\pi(\sqrt{5}+1)n)\sqrt{(n)} \tag{2}$$

$$F(y) = \sin(\pi(\sqrt{5}+1)n)\sqrt{(n)} \tag{3}$$

$$F(z) = \frac{n}{70} \tag{4}$$

Based upon the formulae, a set of generative algorithms for the globally distributed uniform points in three-dimensions is developed in Grasshopper as shown in Figure 2.

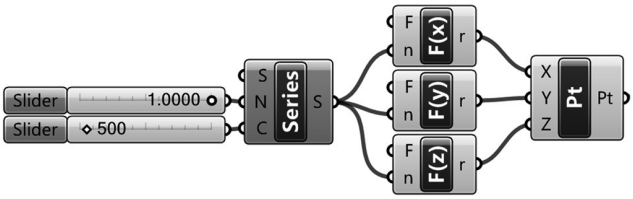

Figure 2. A set of generative algorithms in Grasshopper.

The output of the above algorithms shows their potential to generate an infinite expansion with the increase of the number of points (n) as below.

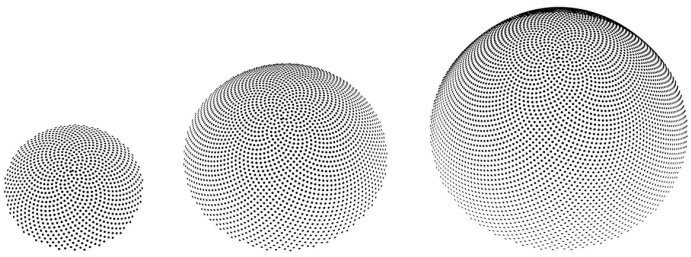

Figure 3. Growth of globally distributed uniform points in three-dimensions.

3. Voronoi diagram: configuration of local geometry

The configuration of local geometry is developed within a parametric Voronoi diagram by optimising the distribution of boundary conditions based on the globally distributed points in three-dimensions. By doing so, an optimised distribution of independent cells fit within the globally distributed geometry.

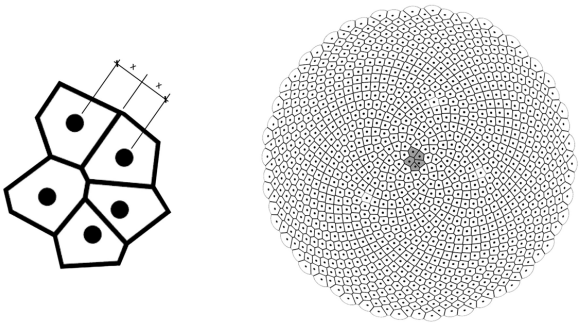

Figure 4. Configuration of local geometry within a parametric Voronoi diagram.

The configuration of the local geometry is generated through an algorithm in the environment of Grasshopper, as shown in Figure 5.

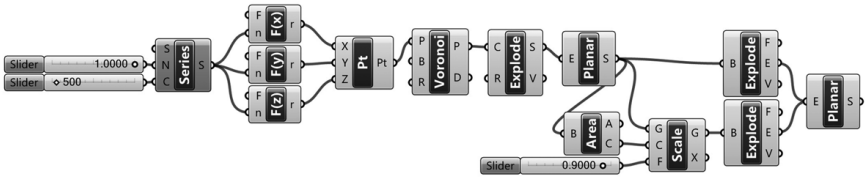

Figure 5. Generative algorithm for configuring the Voronoi boundaries of local geometry.

4. Real-time-responsive system

The design of a real-time-responsive system is initiated from developing various computer applications to produce interactions with environmental stimuli. The integrated configuration is defined through the use of Firefly and the generative algorithm within Grasshopper in connection with an Arduino microcontroller and a photo sensor. The diagram in Figure 6 illustrates how the real-time-responsive system is configured with a photo sensor, an Arduino microcontroller, a breadboard, a resistor, Firefly algorithm in Grasshopper, and motor.

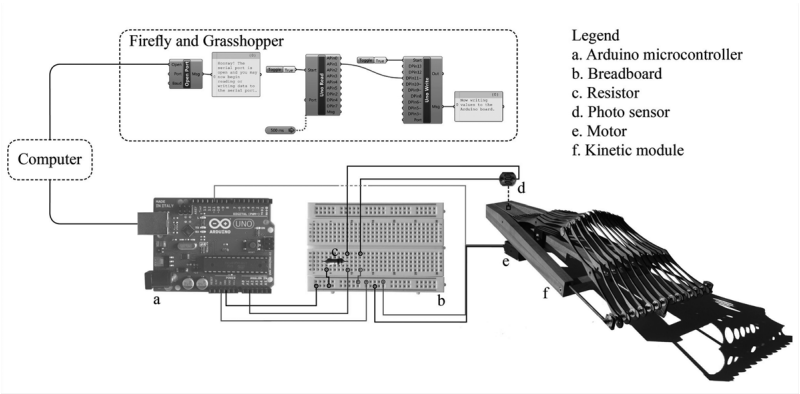

Figure 6. Diagram of real-time-responsive system.

The real-time-responsive system guides the configuration of the global and local geometry of a prototype. Based upon the amount of the changes in photons in sunlight controlled by the user as stimuli, the photo sensor attached to an independent kinetic module sends a signal to the Arduino microcontroller. Real time photo sensory response refers to a one second response time that

is needed for the sensor to read the changes in daylight (Johnson and Andrew 2011). The signal from the microcontroller is converted into data information within Firefly and Grasshopper. The information is used to control the overall size of the global configuration and the number of local geometry based upon the Voronoi diagram generated within Grasshopper as shown in Figure 7.

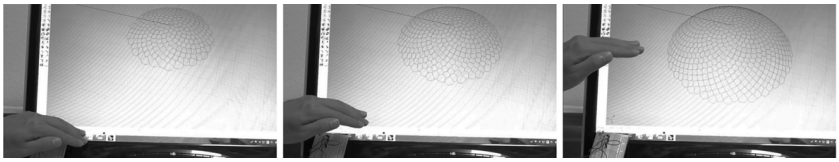

Figure 7. Real time interactive changes of the configuration of global geometry.

Furthermore, the information is used to inform the motor that directs the movement of an independent kinetic module inserted in each local configuration of the prototype as below.

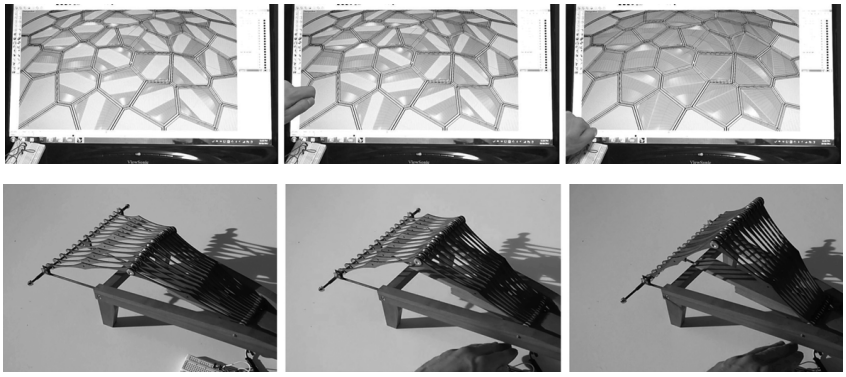

Figure 8. Real time response of individual kinetic module in digital and physical format.

5. Development of individual kinetic module

As for mechanical response, especially regarding the 'performance' of the module, concern is placed on separating the main force from the upper components to reduce rotational stress and the amount of friction caused by the motor. In order to attempt this issue, investigation is placed on the use of a rack and pinion system connected with a motor to provide an immediate response and uniform motion throughout the entire module. The use of this particular system creates a force shown as an arrow in Figure 9 to open and close the upper components. The rotational stress and friction are dampened in the steel rod of the rack and pinion allowing the independent module to

perform in response to the environmental data information sent from the real-time-responsive system. Figure 9 shows the exploded diagram of the individual kinetic module.

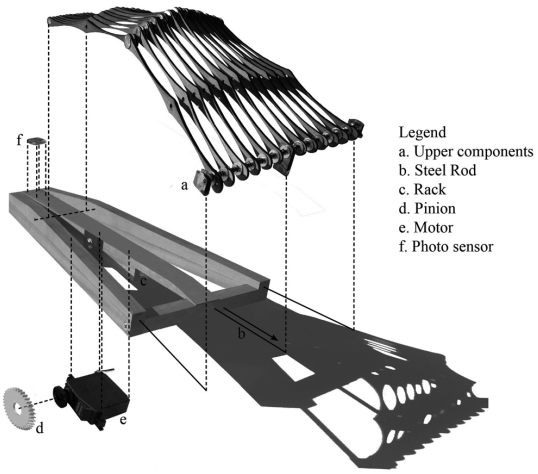

Figure 9. Exploded diagram of individual kinetic module.

The physical implementation of this individual kinetic module with the real-time-responsive system is based on knowledge stemming from multiple fields, including electronics (circuits), mechanics, engineering, and carpentry. The implementation was achieved with the help of machine cutting technologies and the usage of various mechanical parts as shown below.

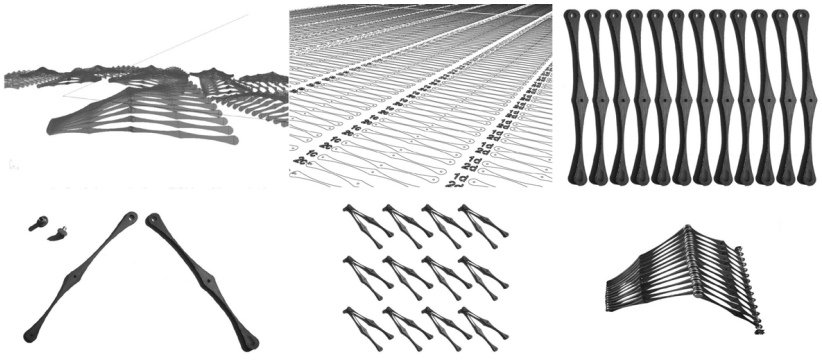

Figure 10. Machine cutting fabrication process.

6. Conclusion and future development

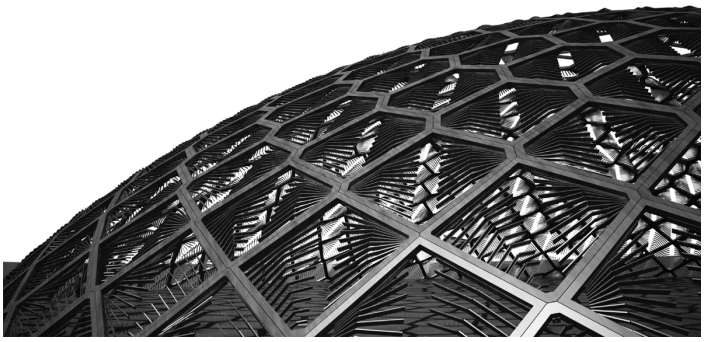

Figure 11. Exterior perspective of the prototype.

A real-time-responsive prototype from the integrated approach provides architects with the potential to develop a "performance-oriented architecture" where an independent kinetic module within a local geometry responds to environmental stimuli in real time. The prototype based upon Phyllotaxis and the Voronoi diagram enhances the quality of its internal space and increases the degree of user interaction. The uniform distribution of points employed in the design of the global and local geometry of the prototype provides structural advantages in the construction of the members.

Figure 12. Interior spatial qualities of the prototype.

The development of a real-time-responsive prototype was successfully completed through the proposed integrated approach toward a 'performance-oriented architecture'. The three-dimensional configuration of Phyllotaxis and

the Voronoi diagram illustrates a promising solution to the initial hypothesis regarding the relationship between structural systems and the natural environment. It is evident that the generative algorithms used for the interpretation of Phyllotaxis and the Voronoi diagram can be applied for the construction of various large expansive systems in the early design stage. At the same time, the real-time-responsive system of the prototype becomes the source for developing various practical applications, not limited to a building, in interaction with daylight, wind, rain, people, or other various stimuli. These include the skin of a skyscraper, the shell of an emergency deployable or nomadic structure, a responsive landscape, or the fabric of a real-time-responsive clothing as shown below.

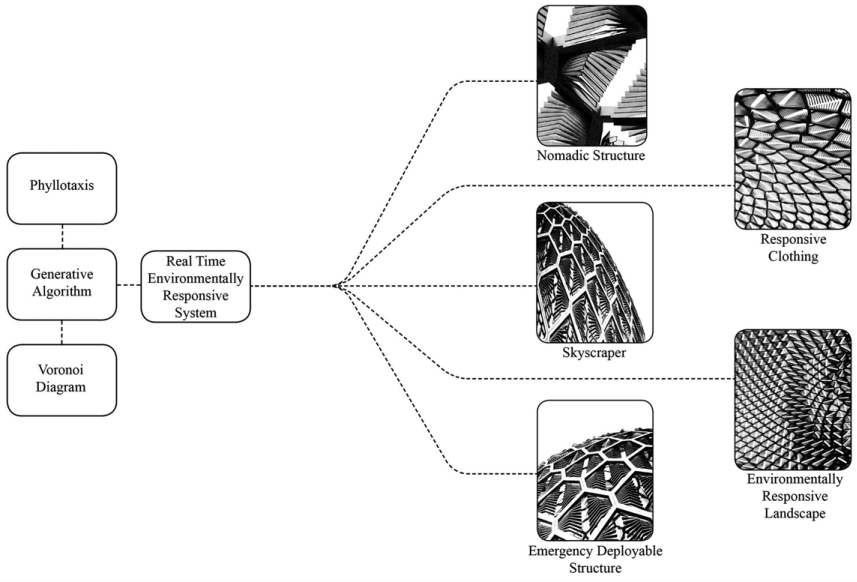

Figure 13. Possible variations of the proposed prototype.

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SPATIAL PERSONALITY FOR HUMAN SPACE INTERACTION

Space for change

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Abstract. Exploring the duality of pervasive computing and architecture in order to propose new models of interaction between people and their built environment. One of the unique "affordances" of digital media is interactivity. This word has come to stand for all manners of engagements between people and things but as McCollough (2004) reminds us the word implies deliberation over the exchange of messages. "Objects" or architecture would be exempt from this mode of communication since, in a likewise manner, we don't interact with a door, we simply open it. However, computing provides a reflexive twist for it is not only the means through which we indirectly communicate with others but also a subject with which we can directly interact. They solicit information and based on the deliberation we ask them for return responses. This quality of computing, especially as it becomes pervasive, has profound implications for architecture and urbanism. When computation becomes embedded into the very materials we build, they along with their nature as inanimate objects become questionable. Our environment itself becomes the interactive subject through which we can inquire about our condition, perform diagnostic tasks or most significantly converse to discover more about our surrounding and ourselves.

Keywords. Interaction; communication; responsive; environment; performative.

1. Introduction

The word interaction has evolved its meaning with time. From an ideology of mere response to a stimuli and sharing experience, and onwards to a technol-

ogy based activity. This transition has intensely influenced the change in the socio-cultural fabric. In architecture, interaction between people was defined by zoning and movement patterns. Now in the digital age, it is aided with technology which is rapidly influencing interaction patterns. It is seen that with just a touch of the fingertip on the surface, messages are conveyed and responses are given back instantly. However it lacks expression, feeling, and gesture that add to human interaction. Is modern day technology limiting our human abilities by arresting human potential? Can we design spaces that bridge the gap of generic surface bound interaction to tangible three dimensional interactions? This investigation seeks to address the need to allow natural order of human interaction with spaces by defining "interaction" between humans and space, facilitated by digital processes and tools allowing optimum use of human capabilities to inquire about ourselves, perform diagnostic and projective tasks or more significantly converse to discover about our surrounding and ourselves.

2. Background study

2.1. DIMENSION OF HUMAN INTERACTION

To develop a new system of interaction, it is essential to explore the dynamics of human exchange and tap into mans' potential, their needs and natural order of using, manipulating and learning from objects and spaces. This process repeats back and forth between dyad and a group in varying degrees of conversation (refer Figure 1).

The various aspects that shape the interaction are:

Nature of human interaction: Includes creating, receiving, manipulating and sharing information.

Choice of interaction: Whether to accept, reject, invite, share, withdraw, observe interaction or even parallel interaction with another while working on a task.

Subject of interaction: Varying from task oriented conversation i.e. task talk to small talk involving building a relation-model with the user.

Varying scales: User interacting at various levels i.e. one to one interaction (I degree), between two (II degree) and one too many interaction (III degree).

Type of response: Verbal (accent, tonal variations) and non verbal interaction (gestures, expressions, manipulation and action) depends on individual personality, habits and traits.

Contextual influences: culture, language, ethnicity, identity, weather and politic climate that influence interaction.

2.1.1. Vision of human-space interaction

Spatial interaction is developed by observing human behavioural patterns to identify new models where in spaces aid and participate in dialogue exchange. "The vision of HCI is to consider ethnicity, age, culture, race and gender of the user, using a varied range of devices that enables human nature of sensing, moralizing, relating, feeling and not just thinking to solve task that on improve the cognitive mind of the individual but to shift focus to varied human needs like story telling, learning to read, finding a friend and extending this to dyads, groups and even macro level of society" (Cassell 2007). This vision can be extended to Human Space interaction where the interplay of surrounding settings and embodied space, along with these varied human parameters, lead to newer levels of interaction.

2.1.2. Technology utilization

Defining and providing natural interaction with such digitally enabled spaces becomes crucial to the success of the mutualist environment. "Interactive technology has physicality of objects – tangible, multiple, minimal-infrastructure that needs to be balanced with generalisability – graphic, dynamic, generic information media" (Merrill 2008). Today's technology relies on vision and limited touch, lacking physicality, restricting wide range of experiences like feeling texture, hearing natural sounds, and gestures like flipping, turning, pouring, waving and expressions. To provide true interaction experience at spatial level, need to understand the natural way of usage, manipulation of objects and spaces by humans. The nature of mutualist embodied space needs to be a transparent invisible medium, relying on less built infrastructure that enables interactive, mobile, flexible, adaptive and changing environment.

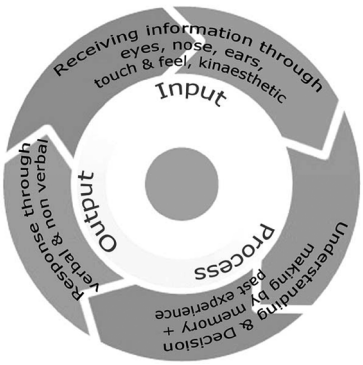


Figure 1. Interaction cycle of a Human

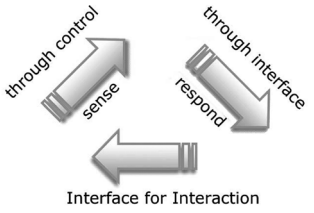


Figure 2. Designing an interface

2.1.3. Spatial personality

The need of the interactive space, to adapt to human personality and habits as well as to allow for customization (Rao 2011) is often neglected as the focus has always been on "efficiency" and not "variability" with allowance for creating "adapting techno-spatial personality", for in human to human interaction this forms the basis of varied communication.

2.2. PREVIOUS MODELS OF HUMAN-SPACE INTERACTION

Previous models of human-space interaction have been modeled around being mainly "visually responsive" to a few human capabilities – movement and touch. The response to every individual is the same leading to repetition thus lacking ap propriate and varied response to the unique individual, dyads or group.

Every decade what is perceived as "contemporary" is cast aside for the new. Change has been a constant factor that challenges design where process and ideas are constantly evolving with people's needs, perceptions and technology. From the primitive models of equating space as flexible mobile machines, like the 'walking city', 'blow out village' and 'enviropill' that controls environments at user's whim (Archigram 1960) to allow users to assemble their environments for learning and entertainment in the 'fun palace' (Price 1960). All these hint at the need for spaces to anticipate change and evolve with time, to respond to needs and changing environments, to allow freedom of customization and control by the user. From being a passive and static space, the shift was towards appropriate, reactive, evolving environments. This led to a virtual reality which failed as we don't just orient ourselves with our mind but with our bodies as well. Artificial intelligence failed, as intelligence lies in interaction and not in a highly developed cognitive machine (Pask 1976). The strong need for a mutualist environment to allow cohesive interaction forms the basis of Human space interaction. Learning becomes crucial for conversing with spaces, so machine and users must learn and adapt from each other. A series of responsive installations created auto-poetic systems that reacted

to cultural, political events and climate of the city (Haacke 1970) while other installations senses everyday noises and responds through the varying lines on screen (Paik 1965). The Internet emerged to be a global social fabric allowing varied cognitive styles, learning patterns, expressive behaviour and flexible for customization (Negroponte 1995). Digital networks are generic in nature with development in HCI; interface became responsive but lacked interaction. Interaction is deliberative and variable in a series of exchanges. The nature of such interactive spaces is to be a transparent medium of interaction where suitability surpasses performance as the key to technological success (Douglas 2004). As interaction models have been evolving with time and context, a study of context-based interaction is explored.

3. Contextual study

Architecture and public behaviour demand different interaction paradigms. The contextual factors are studied and mapped for various range of people against interaction at varying degree. This leads us to rethink the relation of space with user for interaction. By understanding how people interact within a space we can define how people interact with a space by considering the various aspects of interaction like subject, choice of interaction, mode of response and contextual influence will help to create new perspectives.

3.1. SCENARIO 1 – BUILT ENVIRONMENT

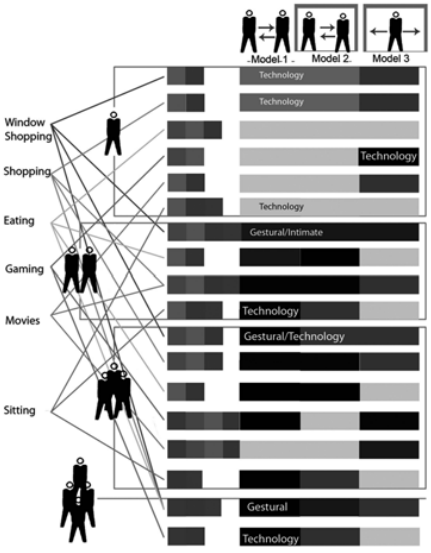


Figure 3. EA mall – built environment

The subject of interaction is highly task oriented while the mode of response is predominantly gestural and verbal. When the activity is not goal oriented usage of technology as a basis for interaction scales up. The third degree scale of conversation is more compared to the second degree. The market space is the contextual influence.

3.2. SCENARIO 2 – COMMUNITY LEVEL

The subject of interaction revolves around task talk for people of similar age groups. Small talk occurs before and after a task while general talk occurs in certain task oriented activities like walking. The nature of interaction is through appreciating, encouraging, explaining, correcting, observing, and imitating information. Technology based conversation is mostly seen in dyads. Type of response is highly verbal. The contextual influence stimulates interaction in people by its multifunctional nature and points of interest.

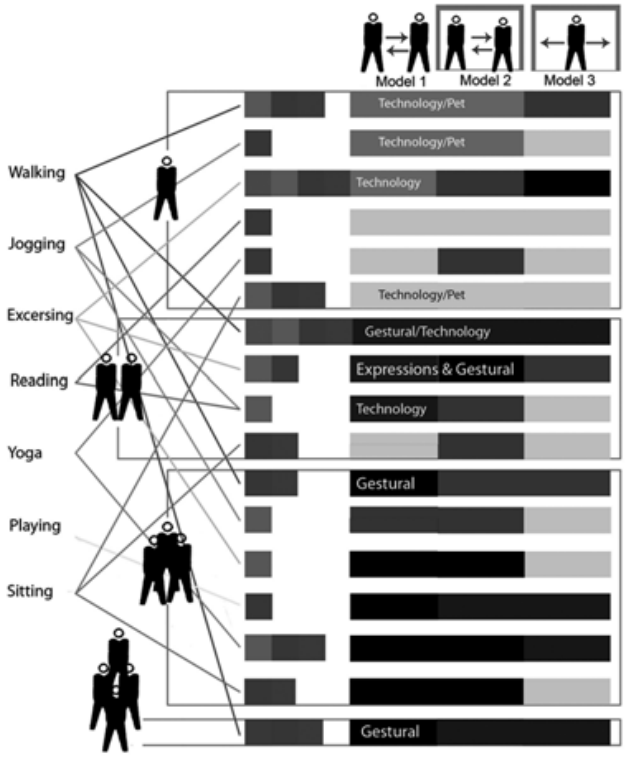


Figure 4. Nageshwara Park – community level

3.3. SCENARIO 3 – URBAN LEVEL

The subject of interaction revolves mostly around general talk while small talk occurs when taking a break from the activity. The contextual influence is inviting human interaction through movement towards area's of high visual activity. Non-verbal interaction is the highest type of response, while verbal is high among the same age group and technology for the first-degree users respectively.

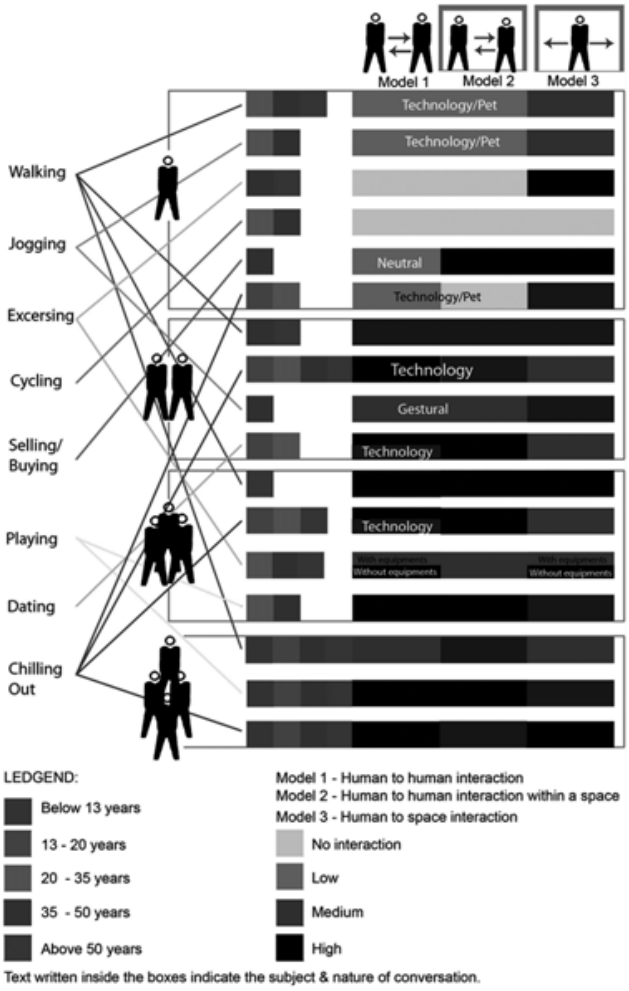
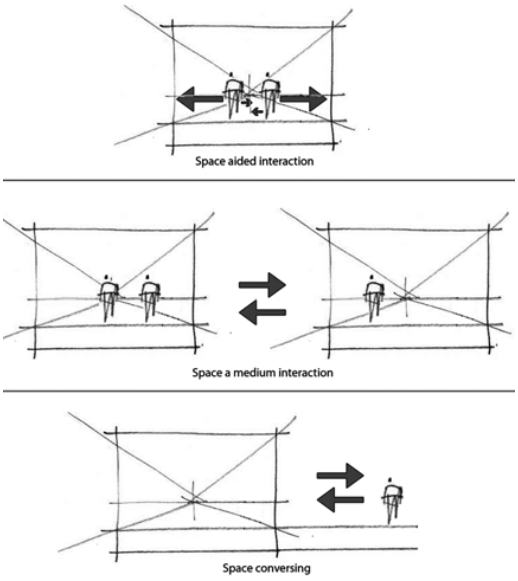


Figure 5. Besant nagar beach – urban level

4. Proposed interaction model



1. Interaction between *people to people with space as an aid* for conversation people in same space.

2. Interaction between *people to people with space as a medium* for connecting people in different spaces.

3. Interaction between *people and space* to enquire about tasks.

Figure 6. Interaction model

5. Methodology

Previous models of interaction by Gordon Pask, Cedric Price and Malcom Douglas have investigated human computer interaction and its various parameters. This research is to explore the third interaction model i.e. spatial interaction with user. The contextual study has opened up paradigms and parameters of interaction, which is analyzed and experimented by the following process.

5.1. INPUT

Information is retrieved by the space through sensing modules. These modules function based on the interplay of the following three characteristics

5.1.1. Visual

The interactive space observes and understands the surrounding spaces in the macro level. The space tracks the user's parameter in terms of number of users, their orientation and activity intensity at system level. The identity, body language, age and gender of each user is mapped at micro level

5.1.2. Sensory

The temperature and climatic variations of the surrounding space is sensed to provide physical comfort. It also allows the users to touch the tangible surface in order to converse with the space.

5.1.3. Sounds

Every day noise and verbal conversations conveys the emotion and mood of surrounding space and user.

5.2. PROCESS

For successful space and user interaction, the former must have a personality as this is required for an exchange of a series of deliberative message exchange and building varied relationship with the latter. This spatial personality can be programmed to be customized and personalized to allow the user to instruct the space. Further more, the decision of type of response needs to be appropriate for an apt response which is worked out with memory mapping of the user and context. The memory mapping is a database of interaction paradigms, which generates a unique digital memory pocket that stores previous interaction patterns by the user. The module senses the user's degree and creates a memory pocket. The type of response and subject of interaction is simultaneously taken as the input. This is analyzed and the nature of interaction is decided upon giving out the response. This process repeats back and forth creating new memory pockets and thus new interaction levels.

5.3. OUTPUT

The scope of physicality and generalisability is investigated for the newer model of interaction. The physicality of the user interface is brought out allowing for spatial expansion and contraction in order to aid in learning, completion of task and conversation. These qualities investigates, through various computational studies, the basic "building blocks" of a space taking into aspect its materialism, structuralism, assembling and ease of usage. The individual module is of a smaller scale allowing physical manipulation that can be operated as a unit on its own and as well as a part of spatial system.

6. Conclusion and further work

The experiment further seeks to investigate into the working of "invisible medium" built into the spatial personality that retrieves input information. The memory mapping of the space is developed by scripting self generating algo-

rithms that create multiple digital memory pockets that develops the spatial personality. Exploring the basic building modules - adaptive mass, flexible surfaces and digital points are woven together to respond with varying degree of physicality. These are iterated and tested with parameters of material, structural and assembling techniques for its physical manifestation. This interaction model allows the user to physically interact with space using the help of computation as a tool. Further more our long term goal is to integrate the first two interaction models derived as an extended function of the interactive space.

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USING THE HUMAN BODY AS AN INTERACTIVE INTERFACE FOR NAVIGATION IN VR MODELS

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Abstract. The use of Virtual Reality (VR) and interactive real-time rendering in urban planning and building design are becoming more and more common. However, the integration of VR in the urban planning process suffers from the complicated interaction handling of the virtual environment. In particular, people unfamiliar to gaming environments and computers are less prone to interact with a VR visualisation using keyboard and mouse as controlling devices. This paper addresses this issue by presenting an implementation of the XBOX 360 Kinect sensor system, which uses the human body to interact with the virtual environment. This type of interaction interface enables a more natural and user-friendly way of interacting with the virtual environment. The validation of the system shows that respondents perceived the interface as non-demanding and easy to use. The implemented interface to switch between different architecture proposals gave a better understanding and spatial reasoning for the respondent. The study also shows that males perceived the system as more demanding than females. The users also associated and compared their body with virtual environment, which could indicate that they used their body during spatial reasoning. This type of spatial reasoning has been agued to enhance the spatial-perception.

Keywords. Virtual reality; XBOX Kinect; perception; navigation.

1. Introduction

The use of VR is perceived by many as having a great potential in increasing the effectiveness and improvement of communication in the decision making process in urban planning and building design (Al-Kodmany 2002, Kjems 2005). VR can facilitate processes so that participants can better understand, identify and analyse problems together to improve their decision-making and the future urban environment. However, VR has not attained the impact and

penetration in planning processes as was predicted. One of the main reasons for this is the complicated interaction handling of VR as claimed by Lubanski (2007). To some extent previous research confirms this, as people within the urban planning processes are very positive to use the VR-medium during meetings with help of an IT facilitator and navigator, but do not have any interest of navigating themselves due to complicated interaction handling (Sunesson et al. 2008). Similar to computer games, navigation and interaction with virtual environments are often performed using keyboard and mouse. Although this type of interaction handling works well for IT-skilled persons and gamers, it can be an interaction hurdle for many of the end-users within the urban planning processes.

The purpose of this study was to find a user-friendly and natural way to navigate and interact with virtual environments in the context of urban planning and building design. In this context, the interaction interface has always been a problem in situations where clients or end-users do not have the self-confidence to handle the VR simulation themselves. Because of the complicated interaction handling, the consequence has often been that the end product from a VR simulation has been rendered images and movies, which the clients feel self-confident to show for the general public. As a result, the full potential of the VR simulation, in terms of enhanced communication and understanding regarding future projects, is not utilised. Fortunately, the developments of new hardware technology have made it possible to now use XBOX Kinect for interaction with the computer. In this case the user can use the body as interface, which has the potential to provide a more user-friendly and natural interface with the 3D-model. To further investigate this, we implemented an interface that uses the human body for navigation in the virtual environment. The aim has been to implement a very simple interaction interface with limited functionality that is user-friendly and feels natural, in order to facilitate a more widespread use of VR simulations. The paper addresses the following research questions: How does the user experience an interactive interface and what is missing? How does the navigation with the body impact user experience and perception of the space? The rest of the paper is organised as follows: The next subsection presents related work; Section 2 presents our implementation of the user interface; Section 3 includes method and validation of the interface; Section 4 includes conclusions and future work.

1.1. RELATED WORK

Using the human body as an interface has been an active research topic in the last two decades within the fields of Human–Computer Interaction (HCI) and Computer Vision (Moeslund et al. 2006, Poppe 2007). Most commonly used

motion capture systems require markers that are attached to the body. Although suitable for animation of characters in games and movies, the requirement of markers can make the systems impractical for use in other situations, such as controlling navigation of VR simulations during design reviews. In this context marker-less motion caption systems present the advantage of not requiring markers for the end users. Marker-less vision-based motion capture systems have tried to provide such a solution, using cameras as sensors (Poppe 2007). However, it was not until 2010 when the XBOX 360 Kinect sensor system was released, that it became affordable to everyone. The Kinect sensors are using the USB-connection to establish communication between devices and the computer. This gives an opportunity to achieve an interaction interface not only for the Microsoft Xbox 360 but also for ordinary computers. By using the Xbox Kinect sensor system to navigate in the VR, we assume that this will give the user a more user-friendly interaction interface. Another interesting possible outcome from using the human body for navigation is that this type of navigation can facilitate a better understanding of the virtual space. When it comes to spatial reasoning the human mind analyses the visual space by comparing its human body with the object in space, and by comparing relations between the different objects (Matlin 2004).

Mullins (2006) tested how different display-systems for virtual environments gave different spatial-perceptions and compared these with the real environment. He found that a Cave gave better spatial-perception than what panorama display-system did and he argued that this was because the human mind uses the body to examine the size of the surrounding environment. Therefore we assume that navigation with the body can enhance spatial-perception while using a VR. Additionally it is also important to understand the limitation in the human visual working memory. Approximately the visual working memory can only store seven information units at the same time (Buziek 2000). The presented information is eliminated after a few seconds if it is not selected by the mind for future knowledge building in the long-term memory. This is something that we have to have in mind when it comes to the context of comparing different architecture proposals. In virtual environments we have the possibility to present the different architecture proposals in the same visual space, by switching between the different proposals. Therefore we assume that on-demand switching between different architecture proposals enhances spatial-reasoning and understanding.

2. Implementation

The release of XBOX Kinect presented the possibility to use it as an interface for navigating in VR, which has the potential to provide a more user-friendly

and natural interface with the 3D-model. The Xbox Kinect (Microsoft 2011) captures the depth information in the scene, which is used for achieving the human body interactive interface for navigation and interaction in gaming environments. The movements, poses and gestures from the viewers' body are captured, encoded and translated into an event that triggers an action that controls something in the game or application.

FAAST (Suma et al. 2011) is middleware that facilitates the integration of human body control with the XBOX Kinect. The FAAST toolkit is emulating keyboard events that are triggered by body posture and specific gestures. The FAAST toolkit therefore facilitates an interface for existing off-the-shelf games that do not provide official support for depth sensors.

We choose to use the FAAST to support integration of human body control. The reason to choose FAAST was mainly because of the easy implementation interface into our in-house developed software MrViz, and that we wanted a pre-study of how the XBOX Kinect could be used. The strength and limitation with the FAAST interface is that it emulates key and mouse events, which limits the human body interaction interface.

In this study we have restricted the interface to a micro perspective of a 3D-city model, where the user views the model from the ground or close to the ground. The following demands on the human computer interaction interface were required: The possibility to walk around by following the ground surface; and the possibility to switch between different models during VR visualisation to show different architecture proposals.

2.1. THE USER INTERFACE

In this section we explain how the human body interface has been implemented into our VR-software MrViz. The first thing a new user has to do when approaching the system is to calibrate or measure the body. FAAST is looking for the calibration pose shown in Figure 1 (column 1). Figure 1 is showing different positions and orientations of joints that trigger events that the VR-software uses. The column 2 and 3 shows poses and orientations that is associated to handle the camera in the virtual environment and the column 3 show poses that triggers the switch between different architecture proposals or models. Furthermore, we used right arm fast forward to stop the walking in the VR-model.

The presented poses were chosen to be as discreet as possible so that people did not feel silly when others were looking. Another choice was to use body movement and not just the arms since we think that people get a better perception of the space.

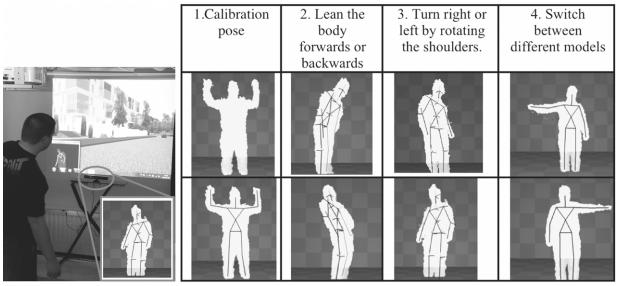

Figure 1. The different human body movements, poses end gestures that trigger interaction and navigation in the VR environment.

3. Method/Validation

3.1. PARTICIPANTS

The study has been conducted on architecture 3-5-year students (n = 18) and civil engineer 3-year students (n = 37) and researchers (n = 4) at a Nordic European university. The respondent groups were selected primarily because they had knowledge and work with urban planning and building design, which is related to this study. 35 of the respondents were male and 24 were female. The respondents' ages ranged from 20 to 61 years, with an average age of 26 years (SD = 6.0). The respondents' reported an average computer experience level of 5.1 (SD = 1.3) as measured on a 7-point scale, where 1 represented little experience and 7 represented much experience.

3.2. PROCEDURE

Participants were introduced to the Kinect interface where they navigated freely in the VR-model of an urban environment. After about 4-5 min during navigation in the model, respondents were addressed by questions of the facilitator (researcher) about the Kinect navigation interface. By doing this we wanted to get the initial experience and how demanding the interface was to learn. The same questions were asked to the respondent in the end of the survey (30-40 min later). The follow up questions were applied to see if the initial experience changed during the procedure in which different tasks were presented. The tasks that the respondents had to perform were related to examine and explore two different urban environments in the context of urban planning and building design. The first task was a volume study of a new building; were the respondent had to answer questions about the volume size and form, see Figure 3a. The second task was to examine and explore a VR-model of three different architectural proposals of rebuilding of the city library in Gothenburg, see Figure 2b–d. In the second task, one group had the ability to do

on-demand switching between the different proposals while the other group had to look at the proposals in a sequence with loading time added between the different proposals.

We grouped the respondents because we wanted to validate the on-demand switching interface and see how this affected the understanding and spatial reasoning. The validation of the on-demand switching was done in the last task, which was to find the proposal they saw before, see Figure 3. During the trials the respondent together with investigator filled in a web-questionnaire. The investigator read the questions to participates and explained the questions in more detail if the respondent did not understand the question. The discussion, answers and explanations on the questions were taped in order to gain more insight into the user experience. Participates also had the opportunity to see the scales and questions on the left to the displayed VR-model were the projected questions were shown. The questions in the questionnaire were related to: user-experience of the navigation; spatial-perception and architectural experience of 3D-models; and finally decision-making in the virtual environments. The questionnaire included in total 54 variables and questions. The study was conducted with a ceiling mounted projector with a screen size of 1.65 × 1.25 m were the users was approximately 2.25 m from the screen with a Field-of-View of 40.25 degrees. The study was conducted on four VR-models, see Figure 2.

Figure 2. a: the first task were participates conducted a volume study of a new building. b–d: the second task was that participant's hade to examine and explored a VR-model of three different architectural proposals and they had to decide on which was the best.

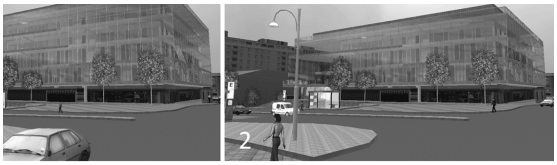

Figure 3. To validate the switching interface, the respondents had to choose which of the options correspond to proposal number 1, which you saw first. Alternative 2 is the correct.

4. Result

Table 1 shows the means and standard deviations (SD) for the quantitative questions related to the navigation.

TABLE 1. Means and SD for non-qualitative question (n = 59).

Variable/Question (*Seven step scale)*	**Mean (SD)**
1.1 How do you experience the navigation? *(Easy = 1, Hard = 7)*	2,07 (0.89)
1.2 How demanding is the navigation? *(Little= 1,* Very*= 7)*	2.15 (1.00)
1.3 To what extent do you think that navigation helps you to understand size proportions in the model? *(*None *= 1,* Very much *= 7)*	4.90 (1.43)
2.1 How do you experience the navigation? *(Easy = 1, Hard = 7)*	2.38 (1.17)
2.2 How demanding is the navigation? *(Easy = 1, Hard = 7)*	2.60 (1.45)

Initially, it can be noticed that most of the respondents thought that the interface of using the body to navigate was easy and not demanding. An interesting observation is that respondents thought it was harder to navigate by the end of the survey. This validates that the method of giving the respondents tasks had made a difference in how they experienced the navigation. Observation during the experiment was that participants had difficulty during the second task when comparing the different proposals. They put a lot of effort to navigate to gain good views for exploring the proposals. However, they still thought that the navigation was easy, but they mentioned some drawbacks with the implementation. 31 (n = 37) of the respondents mentioned "to slow speed forward", 30 mentioned "manipulate the view up and down" and 14 mentioned "view in different direction while going forward (strafing in games). Most respondents commented on the too low speed forward and they mentioned this issue early on during the first task. However, the forward speed was set to 1 m/s because some of the questions were related to perception of virtual space and a higher speed could cause a misleading perception of space. 1 m/s is similar to normal walking, but for future implementation it is important to have the ability to go faster. The respondents also wanted to have more degree of freedom for manipulating the view, such as rotating the view up and down and to look in different directions while going forwards.

During the experiment the investigator observed that females were often more comfortable and convenient to use the body for navigation. This is also evident in the response to the questionnaire on the question How demanding is the navigation, where males mean was 2.4 (SD = 1.3) and female was 1.8 (SD = 0.96). This result shows that male participants perceived that navigation more strenuous then female participants ($t = (2.10\ (57)\ p = .04)$.

To examine the effect of the on-demand switching interface the participants were grouped into two groups; the first group had the ability to do on-demand switching between the different proposals, while the other group had to examine the proposals in a sequence with loading time added between the

different proposals. The validation was conducted by presenting two alternatives of the first proposed building; the first alternative had one floor added and the second alternative was the actual building that participants saw earlier. The participants were presented a task to find the alternative that they saw earlier, see Figure 2.

TABLE 2. Which of the options corresponds to proposal number 1 that you saw first?

Variable	Switch	Load time
Alternative 1.	5	13
Alternative 2. (Correct answer)	8	2
*Chi^2 (1) =7.05, p =0.008	61.5% correct answer	13.3% Correct answer

The results show that the on-demand switching interface gave the viewer the opportunity to perform spatial reasoning from the same visual space, which gave a better understanding and spatial reasoning of the proposal, see Table 2. As presented in Table 1 the respondent thought that the navigation helped them to understand size proportions in the model better. Is it possible that the navigation with the XBOX Kinect and by navigating with the human body enhance the spatial-perception? In this study we found correlations between "how the navigation helped them to understand size proportions in VR" and size related questions and variables, which could be of interest in this topic see Table 3.

To get an understanding of the correlation in Table 3, we sub-divided the respondents into groups according to how they answered question 1.3; Group I, response value 1-4; Group II, response value 5-6; Group III, response value 7. An ANOVA were performed on question 1.3 with its sub-groups 2.1, 2.7, 4.7 and 5.6 as interdependent variables, see Table 4.

TABLE 3. Correlation between question "1.3 *To what extent do you think that navigation helps you to understand size proportions?"* and volume and size.

Variable	**r (p-value)**
2.1 How do you perceive the house volume?	–0.367 (0.004)
2.7 When you made the assessment on the size, to what extent did you compare it to the existing buildings?	–0.343 (0.008)
4.6 How difficult was it to compare the sizes of the two proposals?	0.266 (0.042)
5.6 How difficult was it to compare the sizes of the two proposals?	0.291 (0.025)

TABLE 4. ANOVA between; "To what extent do you think that navigation helps you to understand size proportions in the model?" to different question on sub-groups.

Variable* *1=(Small /very low extent/Easy) 7=(Large /very high extent/Hard)*	Group1 n = 17 Mean (SD)	Group2 n = 22 Mean (SD)	Group3 n = 20 Mean (SD)	ANOVA
2.1 How do you perceive the house volume?	4.29_1 (0.98)	5.10_2 (1.06)	5.09_2 (1.06)	(F(2,58) = 3.81, p = .028)
2.7 When you made the assessment on the size, to what extent did you compare it to the existing buildings?	5.00 (1.90)	5.30 (1.56)	5.95 (0.95)	(F(2,55) = 2.16, p = .125)
4.6 How difficult was it to compare the sizes of the two proposals?	4.47_1 (1.33)	4.25 (1.29)	3.27_2 (1.42)	(F(2,58) = 4.51, p = .015)
5.6 How difficult was it to compare the sizes of the two proposals?	4.00_1 (1.22)	3.30 (1.29)	2.73_2 (1.42)	(F(2,58) = 4.33, p = .018)

Note: Subscripts that differ indicate significant differences at p = .05

5. Conclusions and future work

In this paper we have presented how interaction and navigating in virtual environments with the human body can be achieved. This study has focused on VR visualisations in the context of urban planning and building design, where a user is viewing the model from the ground and close to the ground.

The validation showed that the most of the respondents thought that the interface of using the body to navigate was easy and not demanding. The result also revealed that the on-demand switching interface between different architecture proposals gave a better understanding and spatial reasoning of the proposals. This could be, because the on-demand switching respondents had the opportunity to be in the same virtual space, which decreased the cognitive stress of creating virtual images in their mind of the other proposals and that this helped the visual working memory.

Furthermore, the respondent thought that the navigation with the body gave them better understanding of size proportions in the model. This is in line with literature on spatial perceptions. The human mind analyses the visual space by comparing its human body with the object in space (Matlin 2004, Mullins 2006). Mullins (2006) argued that this was the case when he studied different display systems and why the Cave gave better spatial-perception than the panorama display-system did. The participants also thought that the navigation was easy and not demanding and the analysis shows that males perceived

the navigation as more strenuous then females. Speculatively, this could be because females might have more control over their body movement because they train aerobic etc. Additionally, the participants also gave some comments on what was missing and what limited their experience of the interface, i.e., to slow walking speed and preference for more degrees-of-freedom in the manipulation of the view.

The use of the middleware FAAST in this study has limited the integration and linking to the VR application. But in the future an implementation of head-tracking of the user can give more degrees-of-freedom to the interface. However, this will be done in an API such as OpenNI and NITE or the newly released Microsoft's Kinect SDK. In the future we would also like to compare the interface with keyboard and mouse navigation. Furthermore, we would like to achieve an interaction interface for public environments regarding exhibitions of proposed building designs and urban planning. In such environments or settings the VR software has to give information and feedback to new users how to calibrate themselves to the system.

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DYNAMIC SKIN: INTERACTING WITH SPACE

An inter-media interface between people and space

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Abstract. Space in its physical form provides the major architectural experience for the people inside the space. How people interact with their surrounding space dynamically is a noteworthy research topic. Architectural skin (or "skin" in this project) is the physical interface between people and their surroundings. The skin in this sense represents an inter-media that receive/sense the interactive behaviours of people and react back into space. Further, the skin needs to be mediated and reacted dynamically according to the interaction behaviours. With the case studies, the knowledge of skin design has achieved and then applied to develop three prototypes. In order to achieve the feasibility of skin design for dynamic skins, the multiple channels of input sensors are desired. Thus, a system called dynamic skin is proposed and details of process are evaluated. In order to incorporate the diverse scenario appeared in the cases and prototypes, a distributed system approach such as multi-agent system design is appealing to us. We propose a distributed dynamic skin platform that cannot only provide sufficient interaction between people and space, but also extending such space to the cloud and network.

Keywords. Dynamic skin; multi-agent; distributed; cloud.

1. Background: interacting with space

Space in its physical form provides the major architectural experience for the people inside the space. How people interact with their surrounding space dynamically is a noteworthy research topic. Traditionally, the dynamics appear in the moving of people through the space and the shadow/physical changes caused by the environment to the space itself. With sensory and media technology nowadays, the dynamic interaction between people and space might be literally changed by the behaviours of people inside the space. This provides the motivation of our studies on the *reformation* of "architectural skin". Architectural skin (or "skin" in this project) is the physical interface between people and their surroundings. Space thus represents the physical and informatics both.

Skin as an inter-media between people and space: Skin as an enclosure of building as well as its reflection of human body triggers the awareness of place for the habitants thus the people inside the space. The interaction behaviours between people and space are following the same interaction paradigm of human body then associate and reflect onto the interaction between people and space (Bloomer and Moore 1977). The skin in this sense represents an inter-media that receive/sense the interactive behaviours of people and react back into space. Further, the skin needs to be mediated and reacted dynamically according to the interaction behaviours. The space needs to understand what people behaviour and to perform the reaction.

Ubiquitous interaction and Robotic transformation: In order to accomplish the mediated requirement of the skin described above, two requirements are ubiquitous interaction and robotic transformation (Weiser 1991). As developed from ubiquitous computing, the sensory technology such as embodied sensors in space or motion captures has brought the gestural information into a proximal meaning that allows us to understand what the interactive behaviours of people are. This is the crucial step to achieve the stage of "space understands" (Jeng 2005). Additionally, the robotic transformation mostly developed in robotic or responsive building provides the necessary piece of puzzle to build a responsive skin. With these technologies, interacting with space is realised a robotic structure that can sense the interactive behaviours and react with mechanic transformation. Interaction Scenario Analysis: Even with the technologies above, the skin is still heavily depended on the individual analysis for specialised engineering purpose. These can be seen in the case studies session. Too fragment to have a unified design process that can facilitate and understand the interaction of "interacting with space" and provide useful design information for further design requirement. Scenario analysis in interaction design is brought into our studies to find the obstacle and similarity

between different design cases. Scenario analysis focused on the analysis of events and their consequences based on the interaction occurred in each event and their context. By separating the interaction into a set of scenarios, the interaction paradigm of skin then can be analysed and described for prototyping for evaluation.

Our approach is finding a way to design a dynamic skin utilising the behaviours of interacting with space. With the reviews and case studies, our research concluded with a process model and design techniques. Three skin design prototypes for testing the process model as well as the techniques are conducted and described in the later session. Each skin project has its own motif and system design. By going through four different prototypes, the design process and system concept are then analysed to achieve a unified model for designing dynamic skin and suitable scenario refinement is discussed as well.

2. Case studies

For understanding the basic framework of designing a skin mentioned above, we collected all the related projects from two sources: CUMINCAD and Interactive Architecture Org. The selection criteria are (1) what are the systematic presentations of skins and (2) how these skins interact with people? The cases are classified into three groups as below:

2.1. STRUCTURAL TRANSFORMATION

First group of cases is structural transformation. The responses of skin are via changing the shape of skin structurally. Show Room by Ernst Giselbrecht + Partner is a dynamic façade comprised of a set of programmable white windows. Computer programs and mechanical devices control the openings of window that allow a customisation of the sunlight filters based on the user preferences as shown in Figure 1.

Figure 1. Show Room by Ernst Giselbrecht + Partner, 2007.

This skin is about the variation of components and their structural transformation that can demonstrate the concept required in this research. The variation is done through electricity power and no sensors on the human behaviours to form a truly interaction.

Aegis Hyposurface (Goulthorpe 2001) is a responsive skin that is comprised of a set of units. Each unit has independent (light/sonic) sensor, triangle surface and mechanic structure to form the responses as shown in Figure 2. The variation of skin is done through the translation movement of each triangle surface. The units are also connected to form a surface.

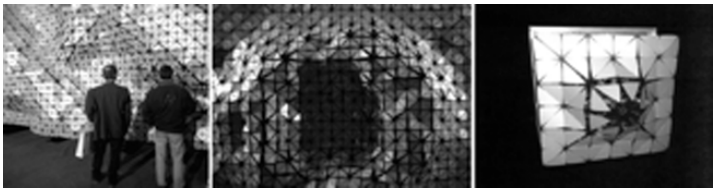

Figure 2. Aegis Hyposurface (Goulthorpe 2001).

2.2. MEDIATED TRANSFORMATION

Another presentation of skin is through its mediated presentation. Tower of Winds by Ito & Associates is a re-design of a water reservoir for the air conditioning system in the mall beneath it. The skin is comprised of a series of reflective plates and surrounding by an aluminium surface. The lights are inserted in the space between the aluminium panels and on the surface of tower. The variation of skin is done by the variation of the intensity and direction of various light sources according to the natural light/weather conditions, wind speed and external noise.

Figure 3. The variation of the skin of Toyo Ito & Associates' Tower of Winds.

Son-O House (Spuybroek 2004) is a place with various sounds composition based on the gestural information of people. Skin in Son-O House comprised of gesture sensors and speakers. People can interact with the skin via both moving in the space and gestures.

Figure 4. Son-O House (Spuybroek 2004).

2.3. INTERACTING TRANSFORMATION

Third group of skins are interacting transformation that are aiming to provide a two-way communication between space and people. Hylozic Soil (Beesley 2007) is a large installation (as shown in Figure 5). The leaves and their stems/branches contain sensors and actuators to react to the behaviours of people. People act and send the signals to the controllers that then actuate the motor to form different shapes physically.

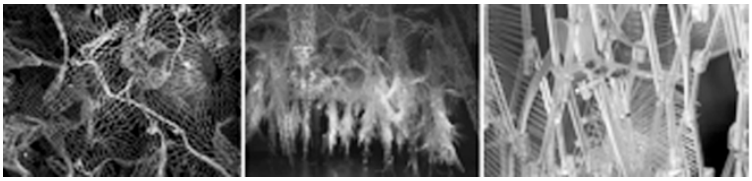

Figure 5. Hylozoic Soil (Beesley 2007).

2.4. ANALYSIS

There are many similarities in these skin designs. Briefly speaking, despite of the physical or mediated presentation, the interaction of skin can be described as "sensing-computing-transforming". Sensing can take people or the environmental information as inputs. And the transformation can be either physical or mediated. Additionally, the connection between units of skin has created another dimensional transformation.

3. Exploration: three skins

3.1. FLOATING SKIN (HSU 2009)

Floating skin is the first project we developed for testing the interaction in a coexisting space. Floating skin contains both physical and virtual information and presentation to utilise the touch and clap action of people.

Interactive Behaviours and Interaction modes The interactive behaviours are basically touch and the skin reacting with movement. Each unit of

Floating skin will either react directly while touched by people or as a chain reaction transmitted from other units.

Sensors and System Model The floating skin is comprised of units that have its own touch sensors and vibration motors. And all units are chained together to form a skin. The translation and rotation of each unit generates the reaction to the touches by people. The system model is shown:

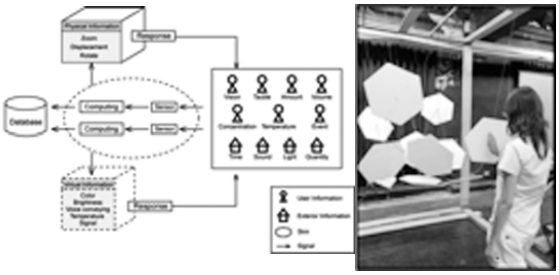

Figure 6. System Model (left) and interaction (right) of Floating Skin (Hsu 2009).

Structure Design The units of floating skin are Hexagonal and connected together by wires, gears and stepper motors to form a skin as shown above. The wires and gears are responsible for the shapes.

Lessons Learned The interaction between people and space lies upon the behaviours people conducted and the transformation feedbacks of skin. Touch is used as a simple gesture and floating structure maintains the varied feedbacks from skin. Shape of dynamic skin did generate different experience and responding to the interaction directly attract more attention from people.

3.2. DANCING SKIN (CHEN ET AL. 2011)

Street Dance is chosen for the variety of dance poses by extremities and show the wave and variety motion of street dance. The motions of extremities of dancer were cooperated with every joint of human body, just like folding form skin that should use structure to make skin motion and do different motion again.

Interactive Behaviours and Interaction modes The interactive behaviours are dancers move and skin reacts. Based on the data collected, the dancer's movements are divided into Chest, Bottom, Hand and Foot. The skin is on the basic of H shapes and constructed by eight H. The H shapes construction is divided into upper and lower limbs, corresponding to the four body parts with joints: hand, chest, bottom and foot, to simulate the motion directions.

The joints are single direction joint and double direction joint. Single direction joint is situated at the top and the bottom end of the structure that

can move back and forth. The double direction joint situated in the middle of the structure, which connected the top to bottom with four junctions, this joint have the ability to move from front to back, right to left two directions, movement through these two kind of joints. For example, the dancer made a wave movement starting from chest pass down to the bottom; the skin may also achieve such motion through the joints and reach the same kind of motion. The system is designed base on interaction between using dancer's continuous body movement for the skin to produce the same motion.

Figure 7. The dancer and dancing skin (Chen et al. 2011).

Sensors and System Model Dancing Skin is comprised of (a) Input: Gathering data detected by optical sensor, heartbeat sensor, Distance Measuring sensor for classification and rule base; (b) Operation processing: After processing sensors classification, and comparing with functions, produces motion information from skin in advance; (c) Output: After obtaining the information, using the skin controller to pass on to the actuation motor, enables the cortex.

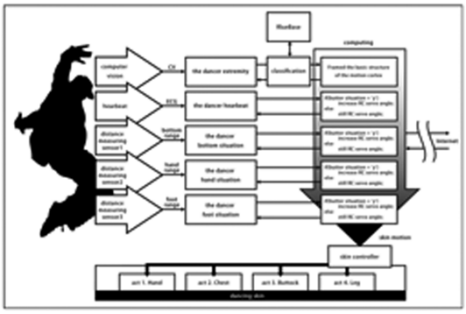

Figure 8. The system diagram of dancing skin (Chen et al. 2011).

Lessons Learned Dancing skin explores the structure transformation with body movement. Using human structure as reference for skin structure, the mapping and reacting between skin structure and people's movement are explored. Such mapping creates a reference for skin's motion design and gearing relation of the skin's joints.

3.3. MUSIC SKIN (JIANG ET AL. 2011)

In music skin, we explore another different input information: sound-based expression (music) and its physical expression (skin). Additionally, the interactions with the skin are divided into two way-of-communication between performer (people) to skin A and skin B to audience (people). These two skins can be two totally different skins in two locations (on stage with performer, off stage with audience).

Interactive Behaviours and Interaction modes Music skins are designed to be the inter-media between people (performers and audiences). Performers and audience' physical changes will reflect onto their behaviours, such as skin temperature, heart beats, voice, body movements and so on. These onstage or offstage behavioural changes can be measured and sensed, then, are utilised for interacting with the skin.

Sensors and System Model Sensor components are classified in three groups: performer, music and audience. Different group will have different technology based on their activities. (1) Performer: the sensors for performers are based on their physical information while performing on stage. Each sensor has its own wireless feature such that it will not disturb the performance. (2) Music: the sensor for music is sonic sensor, using microphone to collect the sound and computing unit as synthesizer to analyse/encode the signals. (3) Audience: sonic sensor for sensing the volume of audience's response and optical sensor for gesture of audience.

With the analysis from performer, audience and dynamic skin structure, we implement a prototype called "Musical Skins" that have double skins system: one is on stage and another is outside the concert hall, namely onstage skin and façade skin. Onstage skin collects the information from performer and music, and then outputs the feedback from the audience.

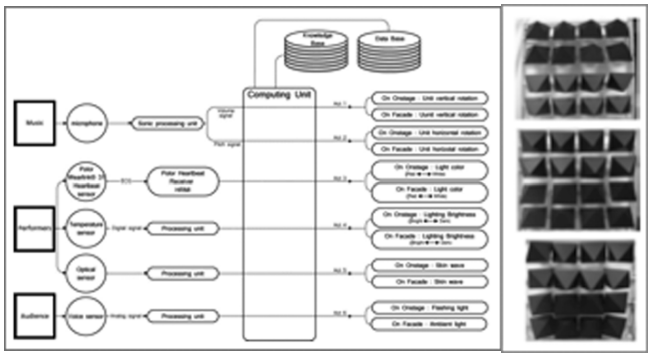

Figure 9. System diagram and physical skin of Musical Skin (Jiang et al. 2011).

Lessons Learned Two separate skins are developed and the connections between these two skins are also explored. The benefits for two skins design are the interaction behaviours for each skin and people are easily identified and can be expanded with different location and fit into different context.

4. System refinement

With the case studies, the knowledge of skin design has achieved and then applied to develop three skin prototypes. A generic system diagram for dynamic skin has concluded as shown in Figure 10. One major concept is in order to achieve the feasibility of skin design for dynamic skin, the multiple channels of input sensors are desired. Additionally, for incorporating further gestures recognition, the system has to be ad-hoc and allows further extension on input. For the output, skin should be divided into skeleton and the skin levels. Each level will have different consideration on the power required and knowledge base for transformation. In addition, the material itself is another important factor. This system framework will be adjusted according to the different scenario.

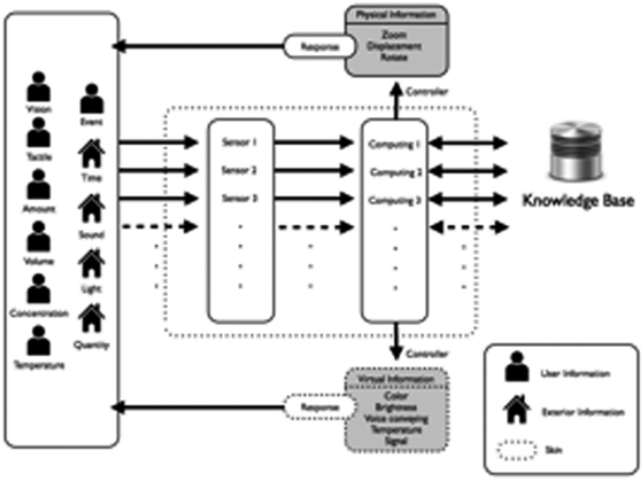

Figure 10. System diagram.

5. Conclusion: towards a distributed dynamic skin platform

Interacting with space is an interesting design research topic. Most of realisation is based on the specific requirement in different context. This research starts with case studies to discover a systematic approach for the skin. Further

with three skin prototypes for testifying the approach. With hand-on experience, a generic system concept called dynamic skin is proposed and details of process are evaluated. In order to incorporate the diverse scenario appeared in the cases and prototypes, a distributed system approach such as multi-agent system design is appealing to us. We further propose a distributed dynamic skin platform (as shown in Figure 11) that can not only provide sufficient interaction between people and space, but also extending such space to the cloud and network.

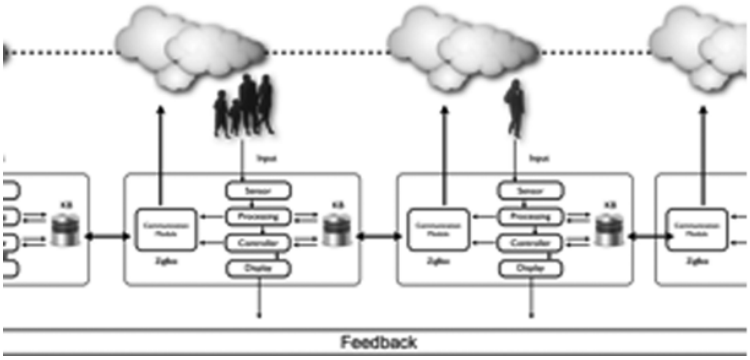

Figure 11. Agent skin system.

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NON-TRIVIAL MEDIA FAÇADES

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Abstract. This paper presents a discussion of contemporary interactive media façades that complements the currently primarily technical framing of this field of research. Media façades, in the form of digitally orchestrated façade illumination, are discussed here as sites of potential encounter and interaction that form part of the public sphere. These aspects seem both underestimated as well as underused as media façades tend to be limited to pre-programmed and primarily ornamental trivial response patterns, or to serving as oversized displays. This paper discusses media façades from an architectural rather than a technological perspective and critically assesses the promises of interactivity as well as implications of such façades on urban public space.

Keywords. Media façades; interactive façades; public space; non-trivial machines; cybernetics.

1. Media façades

Throughout the world buildings in urban centres are increasingly illuminated at night. Façades use a variety of strategies and technologies to increase visibility and to grab attention once darkness falls, ranging from large-scale LED screens (Chanel in Ginza, Tokyo) to LED-based façade illumination systems (UN Studio's Crystal Place, Kaohsiung) to façade projections on building scale (555KUBIK for the Kunsthalle, Hamburg). Illuminated façades with digitally controlled lighting technology, also described as media façades, seem to be particularly popular in Asia. Hong Kong brought coordinated building illumination to the city scale by setting up the "Symphony of Lights" in 2004: Buildings throughout the inner city on both sides of the Hong Kong Harbour perform in a large scale light show featuring dynamic building illumination, lasers, fireworks and sound. While many tourists are impressed and appreciate

the intense visual spectacle, architects seem hesitant to conceive of this aspect of buildings as a domain of architectural designing. Digitally driven façade lighting systems provide new sites and new opportunities for expression, and new ways of creating identity for buildings in relation to their inhabitants and within larger urban contexts. In the majority of buildings equipped with media façades, technological means however seem to have overtaken architects' ability to respond adequately. With innovation cycles in façade lighting technologies being much faster than average building life spans, illumination schemes are added to façades post facto, and often seem disjunct from the architectural forms and spaces they are attached to. Media screens are often merely used to display advertisements or decorative seasonal patterns that do not relate to their 'host' buildings much. Many illuminated façades throughout Asian urban centres that are labelled 'intelligent' merely emphasise building contours with intense and dynamic coloured lighting that serves to catch attention (Figure 1).

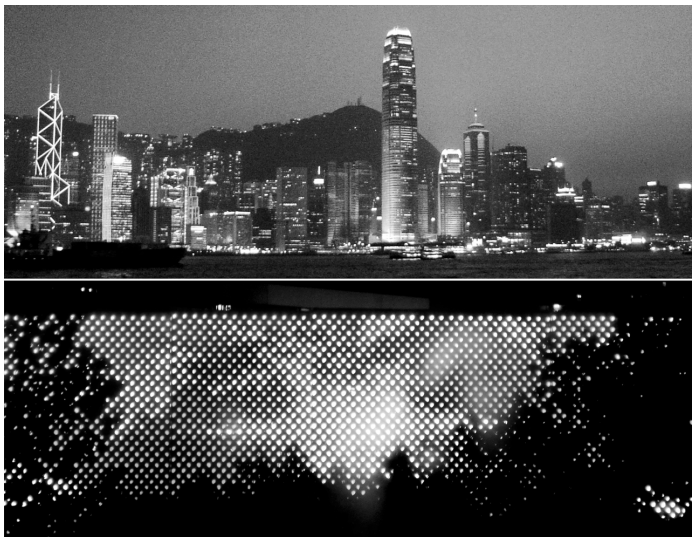

Figure 1. The Hong Kong Harbour skyline (top), a GAP store in Shanghai (bottom).

While an increasing number of new building façades are now equipped with advanced lighting technology, a creative void seems to remain regarding the use of such technology: In Macau, the Grand Lisboa Casino for example boasts an 'intelligent' lighting system consisting of 59,000 LED pixels that, despite the impressive numbers, forms merely a large but somehow arbitrary eye catcher. In Hong Kong, media façades are similarly devoid of content, and

tend to display uninspired advertisements or address an anonymous audience declaring: "Welcome to Hong Kong". In Tokyo, Klein Dytham's UNIQLO building features a street front that is entirely illuminated and shows animated, Tetris-like chunky pixellated patterns next to the retailer's logo. In Shanghai, a high-rise building with a gigantic LED screen across the famous Bund promenade ironically reminds tourists and residents alike to "Protect the environment and save energy!" Few contemporary media façades escape such banality which seems to result from the conception of building façades as mere attention-grabbing display surfaces, following commercial paradigms. Haeusler's (2009) distinction between 'technology' and 'content' in his thorough overview of contemporary media façades suggests that they tend to be developed as empty vessels devoid of and separate from content in analogy to other media, for example generic paper accommodating textual content. This separation of content and medium seems to generate the understanding that architecture is concerned with the 'empty' medium, whereas content is left to either artists or, more commonly, commercial interests. What if media façades were more than displays but a means for buildings to act and thus interact with their environments in more engaging, and perhaps more meaningful ways? What is the architectural, spatial scope of media façades? This paper is based on the assumption that contemporary media façades often do not live up to such architectural concerns. In the following, I argue that limitations in architects' designing of media façades may not be due to technological limitations but to conceptual limitations. In the following, I review previous work in the field and speculate on how digital technology may provide opportunities for interactivity in a cybernetic sense: From a cybernetic perspective, interactivity requires feedback loops integrating human and building behaviour, which could allow for interaction as opposed to commonplace trivial responsiveness.

2. Interactive media façades – a brief review

From building illumination schemes that emphasised building shapes at night since early in the 20th century, illuminated façades in urban environments eventually developed into display surfaces. New possibilities offered by digital technology inspired explorations in dynamically enhancing space through digitally orchestrated light and sound arrangements from the 1960s onwards, as illustrated by Xenakis' 'polytopes' (Oswalt 1991). Early media façades aimed to create relationships between buildings and inhabitants, visitors or urban contexts. Among these early projects was Toyo Ito's 1986 Tower of Winds in Yokohama, which expresses response to environmental parameters in terms of light effects. The tower responds to wind direction and

speed as well as time and sound and attempts to poetically blur the boundaries between response to individual environmental factors – it may in this way be considered an 'ambient building'. Most recently, the incorporation of digitally controlled LED and fluorescent light tubes has resulted in media façades that promise interactivity. The façade of the Allianz Arena soccer stadium in Munich designed by Herzog and de Meuron for example responds to internal activities by changing its colours between red, blue and white to indicate which team is playing on a particular day. It thus allows for a building to express different 'identities'. The D-Tower in Doetinchem in the Netherlands by Spuybroek/NOX is a small sculptural tower that represents citizens' mood - as derived from a daily questionnaire - in coloured illumination. Recent projects have used a variety of techniques to express responses to external factors through media façades. The BlinkenLights installation in Berlin from 2001 could even engage the public by displaying animations and games that were uploaded and played by members of the public.

Research on media façades tends to be framed technologically rather than architecturally and most often concerns implementation and technological questions – what kind of effects can be achieved by LEDs or fluorescent tubes, for example. Haeusler's (2009) comprehensive review of media façades illustrates this tendency as his classification of media façades into categories such as: projection, rear projection, window raster animation, display, illuminated, mechanical and voxel façades takes primarily technical aspects into account. Beyond detailed technological considerations, media façades have also been discussed as a part of social and urban spaces. Based on their applied design work as well as on a review of existing cases, Dalsgaard and Halskov (2010, p. 2280) present eight challenges to the design of urban media façades. In summary, they emphasise the social and integrative dimension of 'media façades' in urban settings and the need to integrate content and medium of expression. They further point out that urban media façades should address diversity of activities and accommodate unpredictability. Dalsgaard and Halskov (2010, p. 2284) remind readers that media façades are part of urban life and call more attention to the long-term changes that such façades may impose on the city. Media façades in this view catalyse new patterns of use and socialisation, and may be seen as "platforms for ongoing development and adaptation" (ibid.).

From a more energy-concerned viewpoint, media façades form an anomaly within the general desire to conserve energy and resources. Media façades waste energy on an increasing scale and create 'light pollution' in urban centres, which has been claimed to have a range of adverse effects not only on the health of inhabitants but also on ecological context. How can media

façades make sense? Selkowitz et al. (2003) call for performance-oriented interactive façades that should respond to changing external conditions and internal needs. They suggest that façade responses could include awareness of harvesting and consumption of energy to maintain visual and thermal comfort of inhabitants. These demands should be answered by 'intelligent envelopes' (Wigginton and Harris 2002) – façades that are both responsive and 'interactive'. Interactivity here seems to refer to the ability of buildings to dynamically adapt to constantly changing environmental conditions but is not further explained. The energy-concerned viewpoint suggests that building façades are part of larger-scale regulatory systems which in their entirety form buildings. From this more systemic viewpoint, responsiveness can be seen as enabling buildings to self-regulate their internal states to the benefit of their inhabitants. Next to serving their inhabitants, this responsiveness leads to improved building performance and can be seen as indirectly extending the life spans of buildings by improving their viability. Interactivity, as further discussed below, exceeds responsiveness in the sense of carrying out pre-planned trivial response to external input. Contemporary media façades, as the above brief review illustrates, are typically responsive, but rarely interactive. The following sections of this paper discuss two aspects of media façades that aim to complement mostly technologically focused previous work with architectural concerns: interactivity and the implications of media façades on urban public space.

3. Interaction

Media façades are often labelled 'interactive' yet there seems limited consideration of the prerequisites for interaction. The following discussion is based on a cybernetic perspective on interaction. The term 'interactive media façade' suggests that building façades can act so as to have an effect on human beings and vice versa. Many existing media façades in this sense cannot properly be considered 'interactive', but merely trivially responsive or reactive as they tend to follow predetermined linear activity patterns. Realities:United's 'interactive' Crystal Mesh media façade for the Iluma building complex in Singapore is a characteristic example, where technological implementation is at the centre of attention and the interactive nature of the façade remains unclear. Fischer and Glanville (2011) argue that contemporary conceptions of interactivity are limited by their reliance on push-button reactive technologies that are best characterised in terms of predictable control and linear causality (Glanville 2009, p. 82). Interactivity in the cybernetic sense, in contrast, is grounded in circular causality, which Fischer and Glanville suggest is "intuitively obvious wherever dynamic stability occurs" (ibid.). Interaction implies sharing, dia-

logue and a mutual in-between and involves unpredictable and serendipitous encounters where interacting parties do not enforce mutual control (Glanville 1998). In architecture, interactivity in the cybernetic sense seems desirable as it allows for mutual learning and adjustment between buildings and inhabitants – which seems appropriate when buildings are required to remain viable for increasingly long time frames to conserve resources. Fischer and Glanville (2011) conclude that much of contemporary interactive art and design remains limited in scope compared to the systems conceived and implemented by early cyberneticians such as Gordon Pask and others, including Ross Ashby and Heinz von Foerster. In these works, technical systems interact with human beings in manners that are not linearly predetermined. This is permitted by feedback loops that allow software not only to respond to an external party, but also to initiate changes itself, such that behaviour can be changed dynamically and unpredictably.

Such feedback loops offer new perspectives on the potential capabilities of buildings: interactive façades can be called 'interactive' only if buildings are allowed and enabled to act and respond to their inhabitants in non-trivial ways. This line of thought dates back to the early pioneering work of Cedric Price, John Frazer and Gordon Pask. In Price's and Frazer's Generator project (Frazer 1995), a reconfigurable building not only responded to its inhabitants' wishes, but also self-initiated changes once the building became 'bored'. Pask's Musicolor software (Haque 2007) not only responded to, but also acted with – and thus truly interacted with – human musicians by being able to initiate actions.

4. Closing the loop: Buildings as actors and interactors

The above review suggests that most contemporary media façades cannot be characterised as interactive. One recent project however has been conceived with a similar notion of interaction in mind: "Ada", an entertainment exhibit made for the Swiss Expo in 2002 that was able to interact with people, using a language of light and sound (Eng et al. 2003). Ada maintained her own set of goals which made her able to both respond and act. Eng et al. (2003) describe Ada as an 'inside out robot' that responded to visual, audio and tactile input, and could express itself through light and sound. Ada's developers thought of her as an organism that was designed to have coherence in the eyes of human visitors. This blurs the boundaries between machine and environment, such that identification of the 'robot' is now dependent on visitors' or inhabitants' perceptions of coherence or identity. Similarly to Pask's Musicolor, Ada was developed for a context "in which humans, devices and their shared environments might coexist in a mutually constructive relationship" (Haque 2007).

Mutuality implies that both parties in an encounter are able to change each other. In the case of buildings, this implies that buildings do not only serve humans, but that they can – within certain constraints – also resist human desires to pursue their own goals. Conversational encounters in a cybernetic sense imply mutual learning in dynamic and open-ended processes. Rather than executing pre-programmed linear response patterns, buildings may be enabled to close interaction loops: Where humans may learn from buildings which habits are most wasteful, buildings may learn about particular inhabitants' comfort zones. Expression of such internal adjustments to the outside could show traces of building inhabitants' lives on usually sleek and uniform corporate façades. A visual expression of a such a scenario can be found in the superflat paintings of the Japanese artist Chiho Aoshima – in particular in her renditions of buildings and urban contexts that blur the boundaries between natural, artificial, buildings, humans, and plants (Figure 2).

Figure 2. Chiho Aoshima: "City Glow, Mountain Whisper",London Subway, Photo by Richard W.M. Jones.

Aoshima presents a world in which buildings seem to be social beings akin to humans. The city is rendered as a society of animated buildings which seem to express themselves through their façades. Aoshima's conjecture of 'living' high rise buildings suggests that urban environments may not be conceived merely as arrangements of inanimate solitary towers but they could also be thought of as societies where conceptions of inside and outside, conceptions of natural and artificial as well as conception of public and private realms merit reconsideration. Taken as a point of departure for a rethinking of media

façades, this suggests an architectural context where façades are not understood as boundaries but as sites of encounter.

5. Media façades in the public sphere

Media façades are typically able to express through lighting patterns to the outside of buildings, but do not make these patterns visible to the inside. The separation of inside and outside prevents conversational encounters between media façades and building inhabitants. Media façades which express mainly to the outside however create a new 'inside' as urban street contexts – particularly in the dense metropoles of Asia - are increasingly enclosed by media façades, similar to the 'inside out robot' Ada (Eng et al. 2003). Media façades can thus not only be examined under architectural viewpoints but also in terms of their implications on urban public space. The often intense and far-reaching visual presence of display-type media façades in particular deserves the question whether such 'sites' should not be considered public urban space. This viewpoint seems to be embraced by the city government of the Brazilian metropolis São Paulo, where advertisements were abolished throughout the city's public spaces starting from 1997. Considered in the framework of Habermas' critique of mass media's influence on the public sphere (1962), contemporary media façades can be seen as a degrading influence as they rarely allow for participation. With architectural concerns for space, interactivity and urban context often absent, contemporary media façades seem to perform as spectacular events in a spectacular society (Debord 1994). Architects seem to prefer to retreat to the domain of the technical challenge, whereas questions of content are left either to artists or, more commonly, to commercial interests. The resulting void can be seen from two viewpoints: either architects and their clients tend choose not to engage with difficult questions of engaging public space, or the urban public tends not to value and engage in offers for interaction. The second viewpoint underlies De Luca and Peeples' (2002) observation that the contemporary public sphere is less based on dialogue but more on parallel dissemination by multiple parties. Based on this observation, De Luca and Peeples (ibid.) propose the notion of the 'public screen' as a metaphor that replaces the notion of Habermas' 'public sphere'. The screen metaphor illustrates public exchanges making up the 'public sphere' that are characterised by a strong emphasis on public dissemination and seemingly little interest in interaction, with processes of listening or receiving in an audience remaining in a difficult to trace private realm.

6. New conceptions of media façades?

In which context could media façades be sites of open-ended encounters on eye level between humans and buildings? One basic requirement for such a context seems to be that buildings need not solely serve humans, but can also be allowed to serve themselves. Goals pursued by buildings and expressed through media façades will only be viable if they make sense economically. In the expectations of Selkowitz et al. (2003), future façades are likely to pursue goals within an energy economy: Façades should aid buildings to harvest and conserve energy, thereby not only serving humans but also increasing their viability and thus their life spans by wasting less energy. This goal contrasts with contemporary media façades which primarily use energy. To interact more directly with building inhabitants, media façades will likely need to be enabled to connect back to the *inside* of buildings. Façades may provide a way to give feedback on energy use to inhabitants through a colour code, for example. Such feedback can serve the double use of connecting to the inside and to the outside of buildings, such that media façades inform those outside the building not only about particular energy use patterns, but also about the human occupancy of such buildings.

Façades, being able to connect inside and outside of buildings, are likely to trace human behaviour patterns in the future and may be enabled to directly or indirectly suggest alternatives to inhabitants' choices. Façades of the future may become sites where buildings, inhabitants and perhaps even an urban public interact and mutually adapt their goals as they search for a shared 'comfort zone'. This resonates with Pask's suggestion (Haque 2007) that goals pursued by machines may be of an evolving or changing nature. Rather than new technology, alternative design strategies for interactive media façades seem to require new views on the potential and possibilities of media façades.

Benyon (2008, p. 5) suggests that members of East Asian societies are able to integrate technology into daily lives in a more seamless fashion than is usual in Western European societies, since distinctions between humans and machines, natural and artificial domains are not made in an exclusive and dualist manner. This offers an interesting vantage point for conceiving buildings that employ media façades to express not only trivial response to external stimuli. Instead, buildings may be allowed and enabled to pursue their own aims and enact their particular conceptions of desirable states. Once buildings are allowed to pursue their own 'interests', they may, within certain limitations, even be allowed to contradict their inhabitants. One interest of buildings may for example be to maintain their viability (and thus, longevity) by balancing energy expenditure and energy gains. For interactive encounters between

buildings and humans to become possible, humans will have to concede some control over their environments to digitally enhanced buildings. In turn, the reward may be built environments that offer new forms of delight through interactive play and unexpected engaging of their inhabitants, and a reinvigoration of public urban space.

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VISUALISING THE DESIGN PROCESS WITH DYNAMIC GRAPH

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Abstract. Design Process is a continuous decision-making movement. Yet, the designer usually executes the process in a jumping way, from state to the other. Nevertheless, this kind of jumping process would cause loss of some essential information, such as a glance of design, or certain process of shape evolvement which designers want to know. Those unrecorded and therefore missing statistics information are very important to the research of design thinking and process. This study employs an animation and comic as research objects. In addition to utilising the methods of thinking aloud and protocol analysis, as well as recording the progress of this experiment, the information is digitalised. By using computer to develop a webpage-interface visualisation cloud system, called Dynamic Graph System which records and collects the evolving data generated from the space design process and stores this information into the cloud database. The system, then, uses the State space as a base, and utilises the derivative Dynamic Graph of spatial style which is evolved from the collected data of the Design Process. By studying and analysing the dynamic graphs, to investigate whether we can acquire more information of design process by using information visualisation approach to record of the evolution of the design process and helped the designers or not. This study intends to explore whether Dynamic Graph System helps and assists the designer to be more efficient in completing his/her work from the interaction between Dynamic Graph System and the designer..

Keywords. Design process; information visualisation; state space search; dynamic graph.

1. Introduction

In general, the designer's design logic usually leaps but is able to be associated with during design process. But it turns into continuous decision-making

when implementing the design process. The designer, however, performs and presents his/ her work in a jumping ways, from state to state. Yet, the discontinuation in design occurs from the leap of the state. This kind of discontinuation causes the designer to miss certain design information.

This exist in the process of continuous action, some hidden state may be closer to the designer's original idea but not obvious. Therefore, finding out how to make continuous observation of the states, which is possibly explore any extension point from the continuous process, as well as developing a new starting point, or a new decision-making point. From the view point of the connected derivation graphs between the states (Figure 1), the graphs could express fractional derivative state messages, which seem to present a dynamic graphic design process.

In the current research of design thinking process and studies, thinking aloud and protocol analysis are the most common used research methods to aid and obtain the information of design process. Nonetheless, thinking aloud and protocol analysis emphasise on and record the designer's explicit inner design thinking. In our analysis, we capture retrospectively the participants' vocal record. Obviously, there is a risk by using these methods, because it is hard for the designer to recall some ideas and the design judgments when designing (Gero and Tang 2001, p. 287). Consequently, this study uses video cameras to record the design process so as to assist any inadequacy of oral analysis. It applies Information Visualisation method to record the evolution of the design process, so as to gather more information on the design process.

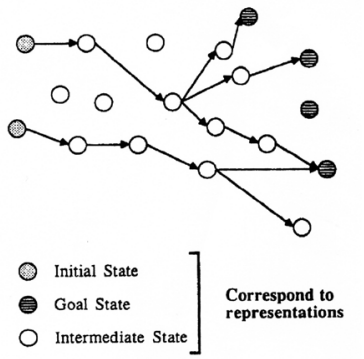

Figure 1. A generic diagram for search (Woodbury,1991)

Information Visualisation has been used in various field. In the past 15–20 years because of the rapid development and cheap prices of computers, it gets more and more consideration and attention to computer-based approach to digitalise information. Despite that, what is visualisation? The definition of visualisation from a dictionary is: to form a mental model or mental image of something. Spence (2007) suggests the process of information visualisation can be simply summarised as Figure 2. He proposes that data and information are different, regardless of any forms of information, through human

interpretation can be converted to graphics. The main task of information visualisation is to transmit the data into information which spectators will discovery later because the data has been encoded into a visualising graphic (Spence 2007).

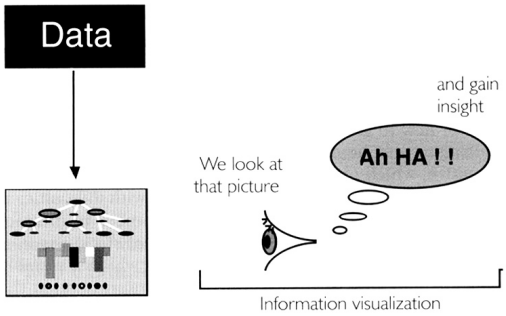

Figure 2. The process of information visualization (Robert Spence,2007)

Therefore, this study utilises digitalisation tool to develop a webpage-interface visualisation cloud system, named Dynamic Graph System. The system records and collects the evolving data generated from the space design process and stores it into the cloud database. The system, then, uses the State space as the base, and utilises the derivative dynamic graph of spatial style which is evolved from the collected data of the design process. This study intends to find the following topics:

1. By using Information visualisation approach to record of the evolution of the design process, whether we can acquire more information of Design process and help the designers or not.
2. Whether the Dynamic Graph System helps and assists the designer to be more efficient in completing his/her work from the interaction between the Dynamic Graph System and the designer or not.
3. What are the differences from the dynamic graph of designer's conscious use of dynamic graphics system to the one that background recorded automatically at a fixed time (one minute once)?
4. Whether the automatic records are surplus information ones or those certain information could be useful to the designer?

2. Literature review

2.1. DESIGN PROCESS

Although the executing design process contains a large number of variables and possibilities, we can induct several general design models from some common design activities to represent the frequent logical structure behind the design activities.

The structure of the design process is constituted by the vertical structure of the continuous acts and the horizontal structure of the decision-making

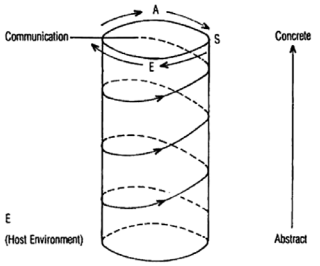

Figure 3. Asimow's model (Asimow, 1962)

production cycle (Asimow 1962). The vertical structure of the design behaviour is the process from abstract to concrete and its horizontal structure shows as a flow status, Analysis → Synthesis → Evaluation → Communication, following by the situation of design messages (Figure 3).

Archer's design process phase model from the viewpoint of design execution, design is considered as a continuous phase actions (Archer 1965). Design contains its sources and commonly-seen types of tasks; as a result, design is described as a general form. The design process is a cycled feedback loop which represents the relationship between actions (Figure 4).

"Analysis → Synthesis → Evaluation" (Alexander 1964) extendedly adds an evaluation to form the cycle. At the beginning, the designer will analyse the problems or the subject to discover the clues of solution. Compositing the experience and related information from database to capture a phase result; furthermore, identify its suitability. Design forms gradually in the repeat adjustment cycle.

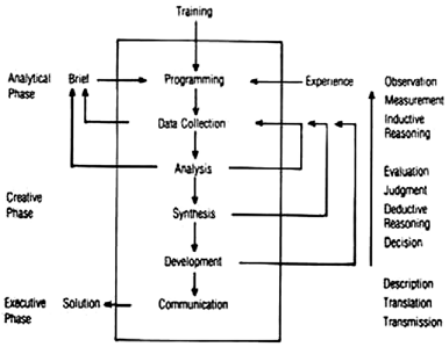

Figure 4. Archer's model

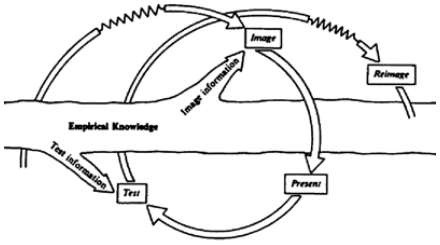

Figure 5. Zeisel's model (Zeisel, 1981)

"Conception → Performance → Test" (Zeisel 1981) is the spiral structure consisted of the cycle of the three actions in the design process. With the progress of the design, the design scope and subject will become more and more narrow and obvious (Figure 5).

"Programming → Design" (Pena et al. 1987) is similar to the process of analysis and then integration. The designer normally plans before design, and use it to do the design.

2.2. DESIGN THINKING

In the exploration and model of design process, it is the design problem to define ill-define problem. The problem space is unclear and no so-called correct answer. Therefore, the research of design starts to see the structure and properties of the design problem to recognise the problem solving of the internal state logics and decision-making process. Newell et al. (1957, 1967) initiates from the perspective of problem-solving behavior, and proposes the message handling theory of problem solving to denote that thinking is a process of message handling. This description and process of analysing human recognition explain the connection of action and consciousness.

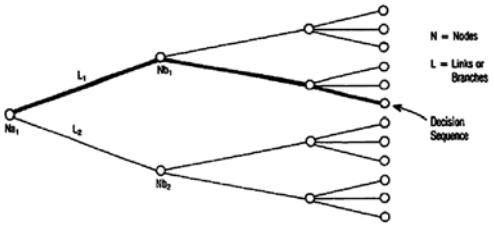

Figure 6. Decision Trees [after Rowe, 1987]

Model 1. Search model (Simon 1969, Rowe 1987) is based on the problem-solving and information processing, design can be seen as a strategically searching process. The form of problem space and the knowledge state is demonstrated as "Decision-making tree" showing all possible results (Figure 6). The designer will use priority-selection and simplified assumption to make his/her process of decision-making easier to handle. Design state shows the variable trend of trial-and-error, and generate-and-test.

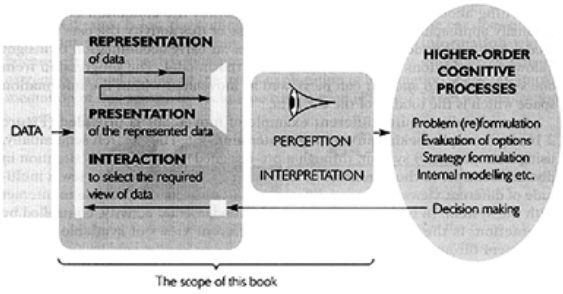

Figure 7. Identification of the interaction with data governed by high-order cognitive processes (Robert Spence,2007, p.26)

2.3. INFORMATION VISUALISATION

Information visualisation refers to the result of data processed after a series of handling transferred into an easier understanding pattern for human brain. It is usually applied into data which could not be immediately discerned. In order to be easily understood, the best way is to shown in figures, because, it's easier for human beings to accept graphics than texts.

Spence (2007) mentioned in his book "Information Visualisation" that identification of the interaction with data governed by high-order cognitive processes (Figure 7). He deems that the process of information visualisation is divided into several phases (Spence 2007). The first phase must collect and store data. The second phase is the representation of data and presentation of the represented data. The third phase is to generate images on the screen by display hardware and graphic engine. The fourth phase is the human identification and consciousness of the image.

3. Methodologies

This study utilises computer to develop a webpage-interface visualisation cloud system, called Dynamic Graph System which records and collects the evolving data generated from the space design process. Furthermore, we employs the methods of thinking aloud and protocol analysis, as well as video camera to record the progress of this experiment to assist on the data capture.

3.1. DYNAMIC GRAPH SYSTEM

Dynamic Graph System is a set of system to record the design process of the designer based on Robert Spence's information visualisation theory and the architecture of the State Space. Users get access from Webpage interface to link cloud database. The designer uploads and downloads its each state of design process in the Dynamic Graph System. Each state is going to record the original file, graphics, and text data, of the designer when design, and then, generate the derivative dynamic graphs immediately for viewing and use of the designer. In the planning and flow of the system (Figure 8), the authorisation defined into user and administrator when logging in. Users can choose to create a new project or open an old project if he/she is not first-time user. They finish the project record as the shown flow of Figure 8. Moreover, the administrator can choose usage management (create, delete, or modify user), or view the projects in the cloud database.

3.2. EXPERIMENTAL DESIGN

Participants Experimental subject is the junior students of Yunlin University of Science and Technology Department of Architecture and Interior Design, who are in certain degree familiar to space design and is able to use Google Sketchup software as the space design tool competently.

The design task In this experiment, we use a design task. The experimenter must design a space, an innovative one hopefully, for the usage of animation and comics. As to the experiment time, Goel (1995) gave his chosen

professional participants more design time, but they have to generate more, including the elements of patterns, scripts, and concepts. On the contrary, Prats et al. (2009) only gave theirs 10 to 15 minutes. The above researches contain human factors, because there is no standard time to imitate natural design process. This research does not limit the design time to the participant after the experimental explanation because this experiment expects to record complete space design process. The experiment is considered finishing until the participants think its space design work is done and store the project. The experimenter spent two and half hours in total to finish the design task.

Experiment set up There is installed Google Sketchup 8 software in the experimenter's computer as the space design tool. Participants know that all of their design activities will be video recorded in all design process. Furthermore, the record of Dynamic Graph System will be divided into two parts: one is the state which is stored consciously by the experimenter, and the other is the graphic change recorded every minute in the background. The participants will be requested to watch the video and discuss their design activities after finishing the design task.

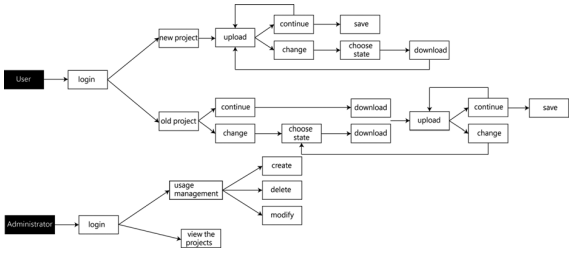

Figure 8. The flow of Dynamic Graph System

4. Results and discussion

Figure 9 shows the recorded derivative dynamic graphs in the Dynamic Graph System which is generated by this experiment. We can clearly see the designer's three different space designs through viewing the dynamic graph and the video record:

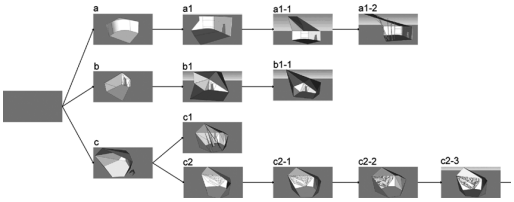

Figure 9. The recorded derivative dynamic graphs in the Dynamic Graph System

1. A series: the development stops at a 1-2. Designers want to develop an innovative space different from the past one. There is an irregular roof and three pillars inserted into the space titled.

2. B series: the development stops at b1-1. Designers attempts to make some changes of the roof style.
3. C series: divided into c1 and c2, but c1 is stopped. Instead, c2 continuously developed to c2-6. Designers of C series use magical space and start from the prism shape. The wall in the space is divided into crushed pieces and removed partial pieces of it to be visible, attempting to make the entire space with the illusion of virtual reality staggered so that space in the shadow looming (Figure 10).

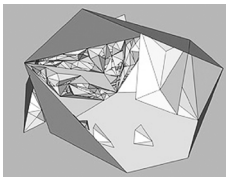

Figure 10. Designers completed work

Additionally, Dynamic Graph System also stores some un-stored graphs in the background. The user only needs to select the arrow between state and the state in Dynamic Graph System to view those not-consciously-stored graphs (Figure 11). We discuss the design activities after the experiment. Designers think that Dynamic Graph System can record ideas when design, such as design at a glance. Because of the record, users can go back to view the dynamic graphs and see what is the problem when there are obstacles. They can get inspiration from viewing the process and go on with the design.

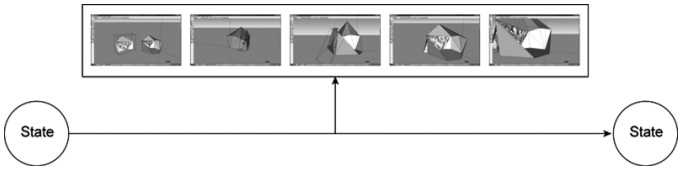

Figure 11. Dynamic Graph System stores some un-stored graphs in the background

Designers reflect that it's a better way to use the discarded shape at each state, like circle or square, as the file snapshot picture for the dynamic graphs because it's more convenient for the design to understand each state presents which shape. With the intention of that, they can choose whichever state to prolong the design more efficiently. In the aspect of the text record, the designer exclaims that the advantage is to record some unexpected ideas to record texts during design process; however, the drawbacks are that designers would like to find design process to some paragraph and perhaps has passed some states. Then, go back and imagine how to write the text record to avoid interruption of thoughts. Designers anticipate storing both the graph and the original file of the background recorded graph in Dynamic Graph System. Designers think the stored graphs are beneficial for viewing the completed design process, for example, deleted certain shapes which were deemed in appropriated at the design moment, until some state stored. He/She has forgotten creative shape but has been deleted. The background recorded graph in Dynamic

Graph System can allow designers reviewing the idea at a glance and being inspired from it. On the other hand, the stored original file can let designers go back to more detailed step of the state and state to carry on design process. For instance, in C series, designers use crushed pieces to make the wall partially visible. They can use these recorded detailed original file to amend and change various crushed shapes design. Designers deliberate that connecting cloud database from Dynamic Graph System can become designer's design database. If designers do same or similar design projects, he/she can use the stored file as the base to modify in the future. Even though for a new subject, he/she can use the files in the database as the foundation for new design ideas, which will make design more efficiently. Nevertheless, some designer also points out that viewing those existing file will block the innovative thoughts of design.

5. Conclusion

Through the record and discussion, this study finds that the use of information visualisation approach can make the design process becoming a series of animation which helps the beating state be recorded in the design progress between the information so that designers clearly see the evolution of modeling details of the design process. Through dynamic graphic design system, designers do not only have the finalised state record, but also reflect on the design process back the missing information after designing. Whether some information (such as the developing features or non-progressing idea) is helpful for the designer or not, these records will facilitate designers to review the design process and thoughts to the future use. In addition, it provides a record of a state so that designers continue to develop ideas.Efficiency in design process, designers interact with others through Dynamic Graph System, can be quickly generated within the design process of uploading and downloading relevant files to the cloud database. This is to say, the designers through dynamic graphics can jump back and forth freely in design process and not worry about file storage problems or the loss of information, such interaction will improve efficiency in design process. When designers apply Dynamic Graph System consciously to generate dynamic graphics which will automatically record within a fixed time (per minute) for verification of the graphics, designers' reaction, perhaps, are wondering or questioning the function of these automatic records. However, when we present automatic records to the user, the user found there were many glances of design ideas. Designers have often forgotten after the completion of the design, but throughout viewing these recorded graphics can evoke their memory, and provide more inspiration to and thoughts. We also find that when users apply Dynamic Graph System in design process. This system can not only become a platform for data storage,

but also can be linked to the other cloud database and shaping this platform as a "design database". In general, each designer has his/her own unique design database, but these unique internal design database is often not explicit. There will be no official record and storage, so through Dynamic Graph System, the date can become explicit information, which is recorded and stored. Moreover, the explicit information will be of great help towards designers themselves or developing ideas in design process. In addition, we found an interesting phenomenon during the experiment, which designers will merge different ideas together. For example, the designer took the a1-2 some portions of its components are combined with b in our dynamic graph a1-2 and b. This phenomenon often occurs in design process, but in Dynamic Graph System currently cannot render such a merger and dynamic graphics, so we will try to follow-up study of the phenomenon of merging records and showing the dynamics of the merger graphics, hoping to record a more complete design process, allowing designers to get more information about the design process.

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COMPUTATIONAL MODELLING OF THE DESIGN CONVERSATION AS A SEQUENCE OF SITUATED ACTS

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Abstract. This paper describes the design conversation as a sequence of situated acts. It distinguishes the research questions that require attention for the computation of a more situated design conversation; in terms of design actions and design interpretations. It presents an architecture for 'more situated' systems and describes some examples of implementation. The limitations and complexities of what has been achieved are identified.

Keywords. Situatedness; situation; design conversation; situated computing.

1. Introduction

The 'design conversation' is a useful way of characterising the interaction between a designer and the design medium (Schön and Wiggins 1992). An architect undertakes conceptual design through a process of both action (moving) and interpretation (seeing). These conceptual design acts can take many forms – perhaps through lines sketched out on layers of butter paper (Gross 1994); perhaps through a click in computer aided conceptual design software (Tang et al. 2011); perhaps through an idea laid out on the canvas of the mind's eye (Bilda et al. 2006). During this conversation designers can be observed to change their conception of the task that they are currently

engaged in (Suwa et al. 2000). A way to identify this change of conception of the task would be to ask a designer "What are you doing now?" at various times throughout the process (Schön and Wiggins 1992, Clancey 199). The designer's notion of what it is that they are engaged in changes through this "seeing, moving, seeing" of the design conversation.

Previous work has explored the notion of design as a sequence of *situated* acts (Gero 1998, Gero and Kannengeisser 2004, Gero 2007). That is to say, actions and interpretations that are a product of first-person knowledge, that are grounded in experience. An agent learns concepts from its experience in the world as well as how to co-ordinate these concepts. This paper is motivated by a desire to connect the way that this co-ordination relates to design: by outlining what is meant by situated design; by describing the questions that need addressing for modelling design as a sequence of situated acts; and by presenting an implementation for a more-situated model of the design conversation.

2. Motivation

Situation cognition is a stream within cognitive science that takes the view that cognition is bound to the interaction of humans with their surroundings and with their own thoughts rather than being separate from other activities. The foundations for such a view of cognition lie with the early work of the experimental psychologists John Dewey (1896) and Frederick Bartlett (1932) and more recently with the research of Lucy Suchman (1987) and William Clancey (1997). That work was based on developing the notions of first-person knowledge based on first-person interactions with the world. First-person interactions have been observed when studying designers as exemplified by the work of Schön and Wiggins and described using the concept of 'move-see-move'.

This paper describes the notions of 'situation' and 'situatedness' as necessary constructs for explaining conceptual design activity. Situations are described as an ecology of concepts that create the current 'world view' of the designer that is a consequence of their past first-person experiences. Situatedness makes explicit the notion that a designer moves between different cognitive states or world-views while designing, and that a different cognitive state changes the way that they see the world. It uses an agent-based model to build a computational implementation of situations. In a situated agent knowledge is tied to its use. Situated design and situations are described to provide a framework for research into modelling design conversation as a sequence of situated acts.

The departure that situated design makes from traditional models of design (design as search, planning or exploration) is that it puts the emphasis on where the designer is at cognitively, the designer's situation. A useful phenomenon for explaining this is the way that designers can look at exactly the same external representation at two different times, and produce a different internal representation of it.

Conceptual designing can be understood as search within a space of possible designs. Some processes that change the space of possible designs are analogy, case-based reasoning and emergence. Situated design provides a unified framework within which these processes can start to be explained. For example, a typical problem of analogy-making systems is not so much producing analogies as knowing which ones are interesting. Through the description of situations we can show why an analogy might be interesting in one situation and not another. In a similar way, situated design allows us to begin to answer such questions such as: How it is possible for a designer to commence a design without all the necessary information being available? How is it possible for a designer to continue designing when all the necessary information is not available? How is it that designers are able to produce novel solutions to what appear to be minor perturbations of existing design requirements? How is it possible for a designer to produce a different design when later presented with the same requirements?

3. Situating the design conversation

In the situated design conversation we can define moving and seeing as tied to the current cognitive state, or world-view, of the designer. *Moving* is concerned with taking design actions within the view of the world held by the designer, whilst s*eeing* is concerned with interpreting the design medium within the current view of the world held by the designer. This distinction of 'occurring within a world view' takes on a more concrete significance once we consider the gap between our notions of designerly activity and current ideas about computation. In the course of this description specific research questions are identified. Implementations that address these questions are then presented.

3.1. COMPUTATION OF 'MOVES' IN SITUATED DESIGN

In traditional generative design systems it is typically possible, for any given state of the system, to exhaustively list the moves available to the system – the space of possible design actions (Langley et al. 1987). Often there are heuristics for search within this space of moves to select one appropriate to this state. We can describe this type of system as selecting actions based upon third-person knowledge, knowledge divorced from experience.

Within the situated paradigm, the actions available to the designer are a consequence also of knowledge that is grounded in experience. One way that this can be conceived is that, based upon experiences, there is a dynamic filter upon the list of available actions (Smith and Gero 2005). The reason why the example with this filter is more situated is that the filter itself has arisen from experience.

This generates the first research question for computationally modelling a situated design conversation: (1) How can an agent's experience in the world lead to learning of design actions appropriate within a situation?

3.2. COMPUTATION OF SEEING IN SITUATED DESIGN

Similarly, the 'seeing' in situated design occurs within the current world-view of the agent. Interpretation in computing is often equated with categorisation, i.e. finding the best explanation for a stimulus from what is available. Within the situated paradigm, seeing the world is about constructing an interpretation that is appropriate to the current situation. Experience leads to learning the interpretations that are appropriately available to an agent. Rather than being able to access the sum total of all possible interpretations, an agent is only able to access those that pertain to the current situation (Kelly et al. 2011).

This generates the second research question for computationally modelling a situated design conversation: (2) How can an agent's experience in the world lead to the learning of interpretations appropriate within a situation?

3.3. A SIMPLE EXAMPLE OF WHAT IS MEANT BY MAKING A SYSTEM 'MORE SITUATED'

In this section the notion of a "filter" learnt from experience is explained using a simple computational example. Consider an unsupervised neural network that is capable of learning from experience, Figure 1a.[1] In this network each node is taken to be a vector describing a potential design feature that the system knows about. As an unsupervised learning network there are rules in place that means the system is able to learn from novel experiences – perhaps learning new nodes, perhaps adapting or removing existing nodes.

In Figure 1a, when the system attempts to interpret something from the design medium, it finds the best matching node within the network. In contrast, Figure 1b introduces a second layer that also learns. The lines between the layers indicate that when a node within this upper layer is activated, only certain nodes within the lower layer are activated.

1 In the examples in this paper a Kohonen Network (Kohonen 1989) was used, but this analysis applies to similar types of network such as ART networks and Hopfield networks with minor modifications to the description

The point of the example is that whilst the lower layer is learning about what can be found within the world, the upper layer is learning about which nodes within lower layer are found together.

An example of the kind of behaviour that such a system leads to can be seen in the Electronic Cocktail Napkin (Gross 1996) where a squiggly line can be interpreted within one state of the system as perhaps a schematic on a circuit diagram, within another state of the system as the roof of factory, and within yet another state as a meaningless squiggly line.

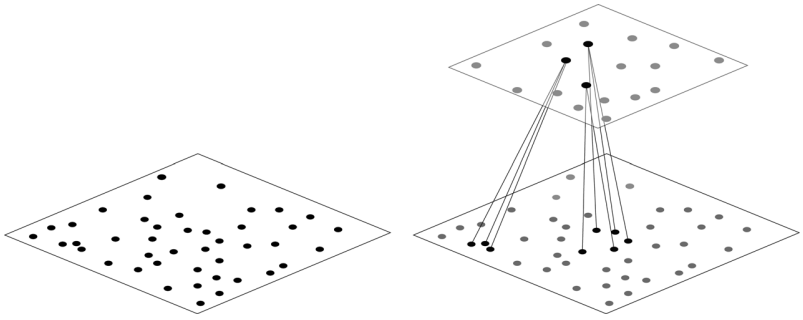

Figure 1. (a) a single layer neural network; (b) a two layer neural network.

The configuration shown in Figure 1b could be said to be 'more situated' than that shown in Figure 1a, because we have introduced a layer of conceptual co-ordination. This is a simple kind of conceptual co-ordination and the example in Section 4 give a hint of some of the complexities encountered and possibilities afforded by more situated systems.

4. A model of a more-situated design conversation

A system that models this situated aspect of the design conversation was implemented, using an architecture of the type shown in Figure 1b. Prior to the design conversation, the system goes through a learning phase in which it learns about its world. It is presented with images of floor plans, Figure 2, and it extracts a series of feature maps from each through sharpening, a mosaic filter and greyscale quantisation on the original image, Figure 3a, to produce a monochrome image, Figure 3b. In this experiment, the 'nodes' within the lower network are these feature maps, and the nodes within the upper network learn how they are co-ordinated.

The current world state that the system is in (the node in the upper layer of Figure 1b) changes the actions that it can engage in; and the interpretation that it can produce. Three different feature maps, Figure 4b, are used to

produce the state of the design medium, Figure 4c. That these feature maps occur together was learnt from the image seen in Figure 4a.

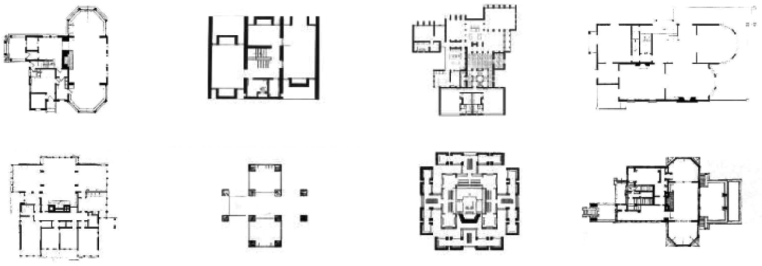

Figure 2. Examples of training set for the system – a sample from 39 floor plans (source: Jupp 2005).

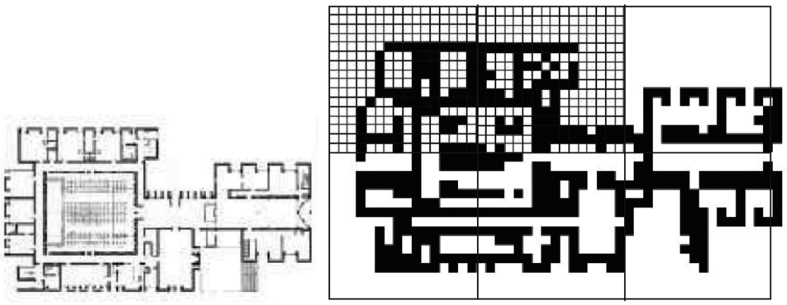

Figure 3. Sharpening, greyscale quantisation and a mosaic filter lead from the original image (a) to the perceived image of a floor plan within the system (b) as six different features.

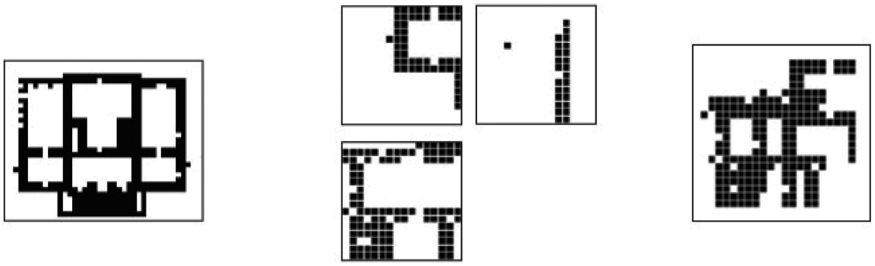

Figure 4. Line detection and greyscale quantisation lead to the perceived image of floor plan within the system as six different features.

The two layers of the system, of the type seen in Figure 1b, correspond to these 16 × 16 pixel feature maps on the lower layer, and the groupings of these

feature maps on the higher level. The use of an unsupervised learning network with two layers presents one exploration of question (1), in that the relationships are all learnt through the systems interaction with its world. Regardless of what is presented to the system in its learning phase – be it floor plans, circuit diagrams or modern art – the system creates these feature maps and learns which of them are found together.

This system holds knowledge about many different floor plans (e.g. the 8 seen in Figure 2 and 31 others). When either an action or an interpretation is made, only a part of this knowledge is made use of. The combination of different feature maps to change the design medium, e.g. to produce Figure 4c, is done through random layout upon a canvas. However, the space of possible design canvasses is limited by the situation, the node currently active at the topmost layer of the system. Similarly, when the system comes to interpret its own work, it doesn't make use of the features from all 39 known floor plans, i.e. it doesn't simply make the best categorisation possible. It interprets within the bounds of the current situation.

5. Discussion

5.1. CHANGING THE SITUATION

An obvious limitation of this description is that without changing situations, the set of possible actions and interpretations doesn't change. However, in designers, we see that the situation changes frequently – especially in the early stages of conceptual design (Suwa et al. 2000). Consider once more that a designer's notion of "What I'm doing now" changes throughout the design conversation. In terms of the model, this is the issue of how can we model the movement between different nodes at this topmost layer of the system.

This raises the third research question for computationally modelling a situated design conversation: (3) How is it that a system: (a) learns when to change the situation; and (b) learns how to moves to a situation that is more appropriate when it does change the situation?

Computational explorations were made of both parts of this question. The idea used in addressing question 3(a) is that the situation changes when failure of some kind is experienced. In this model, the idea of boredom was introduced. If the system stayed within the one situation for too long it started looking for low-level cues (feature maps in this model, but representative of perceptual cues) that might trigger other situations. For example, if it sees, within the design medium, that the layout of two feature maps inspired by a Louis Khan floor plan produces a shape, that is reminiscent of a Palladio floor

plan, then notions from this higher level concept are introduced into the situation. In this way, the model moves between different situations as the design conversation progresses.[2]

In answering question 3(b) the notion of an implicit expectation is introduced. If the nodes within a situation are considered as explicit then the notions of spreading activation (Anderson 1983) and similarity (Tversky 1977) can be used to suggest that nodes close to these within conceptual space (Kelly et al. 2011) are more likely to be activated than those that are further away.

Consider Figure 5, which shows two different scenarios. In the first row, a system is taking actions using a shape (a square) which is labelled as an explicit concept. It then lays out this concept in a particular configuration when drawing with this concept. When it looks at the results of its action, it sees five instances of this same shape to produce an interpretation that uses a structuring of a single concept. In the second example however, the system does much the same thing with a different explicit concept, however it sees a new shape within what it has drawn. How is it that the system is able to distinguish when one or the other occurs?

An implementation was produced to explore this phenomenon. The system shows how similarity to implicit concepts within the lower layer can lead to changes of the situation, in the higher layer. The similarity between expected concepts and interpreted data is a key part in resolving questions of the type raised by Figure 5.

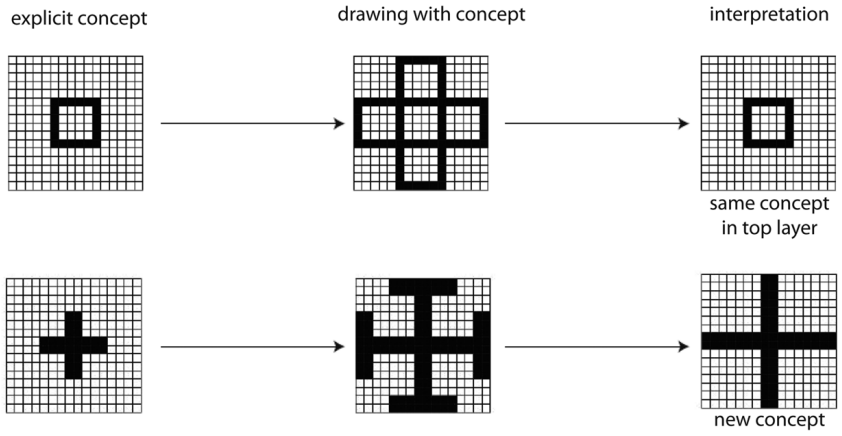

Figure 5. Two different responses to a novel feature emerging in the design medium.

2 Videos of the model in action are available through correspondence

5.2. A SITUATION IS MORE THAN JUST A FILTER

The difference between Figure 1a and Figure 1b is that there is a "filter" applied to the nodes available during interpretation and action within the latter. In a "classical concepts" way of thinking, each of the nodes within a system is a discrete entity and is always used within the same way. In contrast to this, consider that when a system is interpreting, the nodes that are available potentially affect each other. For example, consider that a single node within Figure 1b might be a part of two different situations – and that the node is used differently in some way depending upon which subset it is a part of. Kelly et al. (2011) presents approaches to how this may be implemented.

This problem is recognised as the fourth research question for computationally modelling a situated design conversation: (4) how is it that concepts within a situation perturb each other?

6. Conclusions

The questions posed by this work have asked how the conceptual co-ordination learnt during experience affects design action and interpretation; how situations change during the design conversation; and how concepts within a situation perturb each other. The implementation described gives an idea of the kind of research that can be conducted to move towards more-situated models of the design conversation.

Our computational constructs are moving closer to our conceptions of designerly activity but still have a way to go to match these notions (Gero 2007). These notions of designerly activity, described as situated design cognition are founded on first-person knowledge gained from experiencing the world through interactions with it. This paper has identified four key research questions that need to be addressed in the computational systems of the future if they are to become aids that change their behaviour as the designer learns through doing. Early explorations within a two-layer neural network architecture have demonstrated how research into these questions may be conducted and suggest ideas for addressing them based on existing computational implementations that demonstrate how situated design acts occur.

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SPATIAL ABILITY, CREATIVITY, AND STUDIO PERFORMANCE IN ARCHITECTURAL DESIGN

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Abstract. Architectural design is a multifaceted discipline that requires many abilities, in particular creativity and spatial ability. In order to identify the relationships among spatial ability, creativity, and studio performance, an exploratory study was conducted at one Midwestern university in the USA. Twenty-one freshman architecture students participated in the study, which involved three tasks: (a) the Torrance Test of Creative Thinking that measures fluency and originality in creativity, (b) a group of general spatial ability tests, and (c) the computer-based Architectural Spatial Ability Test. Students' scores on the tasks were compared with their studio performance grades using SPSS. Results show that studio performance correlated with the ASAT but did not correlate with the TTCT or a group of general spatial ability tests. These findings indicate that a student's performing well does not necessarily mean that she or he can generate many different alternatives (fluency) or original ideas (originality) nor that the student possesses general spatial abilities. The findings show the complexity of architectural design components and reveal beginning design students' architectural abilities.

Keywords. Creativity; spatial ability; architectural spatial ability; studio performance; architectural design education.

1. Introduction

Architectural design is a multifaceted discipline requiring diverse abilities, in particular creativity and spatial ability. One of the goals of architectural education is to nurture students' capacity to generate creative solutions. In addition, because the ultimate aim of architectural design is to build three-dimensional structures, the ability to read, interpret, and visualise spatial information – spatial ability – is important (McKim 1972, Oxman 2002). The basic com-

munication media of architecture information is either two-dimensional (2D), such as floor plans and section drawings, or three-dimensional (3D), such as physical or computer-generated models.

Despite the significance of creativity and spatial ability in architecture design, few studies have addressed the way they relate with each other and with the overall studio performance as many researchers have pointed out (Ho et al. 2006, Park et al. 2006). This paper discusses beginning architecture students' architectural spatial ability and its relationship with design creativity and studio performance.

2. Background

2.1. SPATIAL ABILITY

Spatial ability generally refers to the "skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information" (Linn and Peterson 1985, p. 1480). Several categories of spatial ability have been identified in term of the nature of measurement, such as Linn and Peterson's (1985) three categories—spatial perception, mental rotation, and spatial visualisation. Spatial ability is often regarded as related to mathematical and logical reasoning ability (McGee 1979). With regard to the architectural design domain, however, a literature review of spatial ability shows two limitations: (a) a lack of studies conducted in the design domain and (b) the use of excessively simple figures for a test that may be far from spatial ability in the architectural domain.

Most tools used for spatial ability tests usually consist of simple figures (cf. Shepard and Metzler 1988), which are far less complex than architectural 2D and 3D media. Thus, a gap in measuring specific architectural spatial ability may result, and the test results may not tell much about spatial ability in the architectural domain.

2.2. ARCHITECTURAL SPATIAL ABILITY

The Architectural Spatial Ability Test (ASAT) was developed in response to the lack of tools to measure the spatial ability of architecture students specifically. A computer-based test, the ASAT was developed by the author of this paper in 2006. Following 10 years of observations of expert and novice designers, a strong hypothesis emerged: Designers who are adept at reinterpreting 2D information in 3D space and vice versa tend to be more creative in architectural design than those who are not.

With members of the Creative Design and Intelligent Tutoring System in Korea, where the author worked as a researcher, a task called the Plan-

Perspective Matching Task was developed to measure part of architectural spatial ability. The pilot study in 2006 showed a potential correlation between architectural spatial ability and design creativity, but it also highlighted two problems to be solved: the need for a valid measurement tool for creativity and for a less difficult spatial ability task.

To illustrate, for the pilot study a small design-solution task was used as a measurement of design creativity, but a lack of internal consistency occurred among the task evaluators as a result of subjective criteria, raising the need to use a validated measurement of creativity.

2.3. CREATIVITY TEST: TORRANCE TEST OF CREATIVE THINKING (TTCT)

Among creativity tests the Torrance Test of Creative Thinking (TTCT) has been studied and used by researchers for more than 30 years, and its reliability and validity are reported as high (Kim 2006). The TTCT is also considered the best predictor for adult creative achievement (Torrance and Wu 1981). In addition, it has the largest norm (Kim).

Torrance (1966, p. 6) defined creativity as follows:

> "a process of becoming sensitive to problems, deficiencies, gaps in knowledge, missing elements, disharmonies, and so on; identifying the difficulty; searching for solutions, making guesses, or formulating hypotheses about the deficiencies: testing and retesting these hypotheses and possibly modifying and retesting them; and finally communicating the results."

The TTCT is based on divergent thinking creativity theory (Kim 2006), which is a part of the model of the structure of intellect, proposed by Guilford (1959). He suggested five groups of intellectual abilities which contain divergent thinking and convergent thinking abilities. Divergent thinking involves producing a variety of solutions to a problem (Guilford). It is appropriate for tasks without a correct single answer and is not completely determined by the given information (Potur and Barkul 2009).

The TTCT has two versions: Thinking Creatively with Words (Verbal) and Thinking Creatively with Pictures (Figural) (Torrance 1990). The scoring of the TTCT is called the Creativity Index, which is the sum of the average of five creativity dimensions (fluency, originality, abstractness of titles, elaboration, and resistance to premature closure) and 13 creative strengths. The creativity index can be compared to the national average for the age (or the grade), so it informs the subject's rank in the nation compared to the average for the age (or grade).

3. Research method

Data collection was performed in June 2011. A total of 21 freshmen (16 males and 5 females) participated. Recruited from a summer architecture studio course in one Midwestern university in the United States, participants were homogenous in terms of their previous knowledge of architecture.

3.1. MEASURING TOOLS

A total of three measuring tools were used: (a) TTCT, (b) ASAT, and (c) three general spatial ability tests. A figural test was used because it was reported fair in terms of gender, ethnicity, and culture as well as language (Kim 2006). Because five international students participated, using a figural test appeared more appropriate than a verbal test.

General spatial abilities were assessed with three tests: the mental rotation test (Peters et al. 1995), paper folding (Ekstrom et al. 1976), and visualisation of viewpoints (Guay and McDaniels 1976). According to Linn and Peterson (1985), spatial ability consists of three abilities: spatial perception, mental rotation, and spatial visualisation. The paper folding test and visualisation of viewpoints measure spatial visualisation; and the mental rotation test measures mental rotation (McGee 1979).

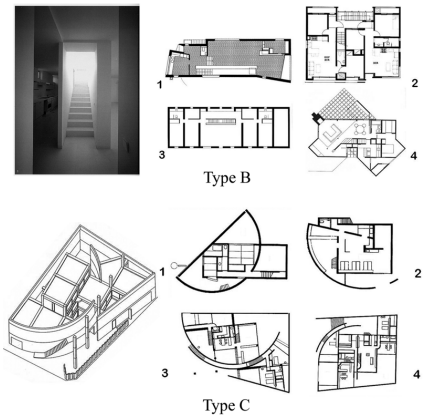

Figure 1. Example of Architectural Spatial Ability Test.

Architectural spatial ability was measured by the ASAT to measure domain-specific spatial ability in architectural design. Through a check of reliability and the degree of difficulty, 15 multiple-choice questions were finalised and divided into three types, depending on the type of architectural drawings used:

(a) A 2D floor plan is provided, and then participants are asked to select a corresponding 3D picture of the space; (b) a 3D image of a space is provided, and then participants are asked to select a corresponding 2D floor plan of the space; and (c) a 3D-perspective view of one architectural structure is provided, and then they are asked to select a corresponding 2D floor plan of the space.

The format of the test offers two iterations of question and answer. To illustrate, a 2D floor plan is shown for 30 seconds; then the image is withdrawn. Next, multiple similar 3D pictures are shown for 50 seconds, and they are asked to select the one corresponding with the original floor plan. Then the question is shown again for 15 seconds, and the image is withdrawn. Multiple answers are shown for 25 seconds, and during that time participants are asked to choose the matching one and write the reason for their decision.

3.2. EXPERIMENT PROCEDURE

The TTCT was administered in the architecture library in order for each student to have her or his own table and a quiet environment. The ASAT and other general spatial ability tests were conducted in a computer lab adjacent to the library. The order of tasks was (a) TTCT, (b) ASAT, and (c) three general ability tests. The rationale for this order was that the TTCT measures fluency and originality, so administering it at the beginning of all experiments when test-takers would not be fatigued from other tasks seemed logical. The pilot study showed that students enjoyed taking the ASAT; therefore, it was provided in the middle of the whole experiment in order to maintain participants' interest. The three general spatial ability tests were conducted at the end of the experiment. Students had a 15-minute break between the TTCT and ASAT; thus, the entire experiment took 85 minutes.

3.3. STUDIO PROJECT

Participants' studio performance was evaluated by their instructor with a letter grade. The student project was a house design for an art centre curator considering "the inter-relatedness of two- and three-dimensional thinking and representations" (from syllabus, p. 1). Students were asked to design the house after studying the design principles of two early modern houses: Villa Stein de Monzie by Le Corbusier and Moller House by Adolf Loos. The suggested hypothetical location of the student-designed house was to be in proximity to these two houses. The final outcomes of the project were a set of drawings and a physical model of the designed house.

4. Results

4.1. DESCRIPTIVE ANALYSIS

Collected data were analysed using the SPSS program. A correlation analysis was used to identify the correlation among TTCT, ASAT, general spatial ability tests, and studio performance grade. Instead of the raw creativity index value, a National Percentile with grade was input and calculated. In addition, instead of the raw scores on the ASAT, general spatial ability tests, and studio performance grade, participants' converted scores on a scale of 100 were used. Table 1 shows the descriptive analysis of the TTCT, ASAT, three spatial ability tests, and studio evaluation. Figure 2 shows the Standard Deviations (SD) of those scores.

TABLE 1. Descriptive Analysis of TTCT, ASAT, Spatial Ability, and Studio Grade

		Minimum	Maximum	Mean	Std. Deviation
	Studio grade	72	88	83.33	3.582
	ASAT	46.67	100.00	72.06	13.60
	Mental_R	4.17	83.33	49.17	23.20
	Paper_F	30.00	90.00	65.95	15.78
	Visual_V	33.33	95.83	66.07	19.29
TTCT	Fluency	15	90	49.24	20.66
	Originality	1	87	42.43	29.89
	Abstractness of Title	6	93	42.38	24.59
	Elaboration	11	90	43.29	20.63
	Resistance	13	97	39.95	28.11
	TTCT Creative Index	8	90	46.38	26.74

The average TTCT scores of the students were lower than the National Percentile for the same grade at 46.38 (the national average is 50, Figure 3). Students' TTCT creativity index ranged very broadly (from 8 to 90). Among the five creative dimensions, the average 'fluency' score was highest, followed by 'elaboration'. Average ability to 'resist premature closure' was the lowest among the five. When comparing SD, students showed a more stable ability in 'elaboration' than in other creative dimensions; and the ability to generate 'original ideas' was the least stable and diverse among students.

In the three spatial ability tests, students felt the mental rotation the most difficult. Mental rotation also yielded the highest SD, which indicates that the ability in mental rotation was the least stable among students.

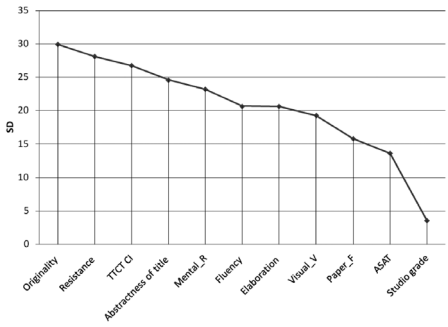

Figure 2. Standard deviation TTCT, ASAT, spatial ability, and studio grade.

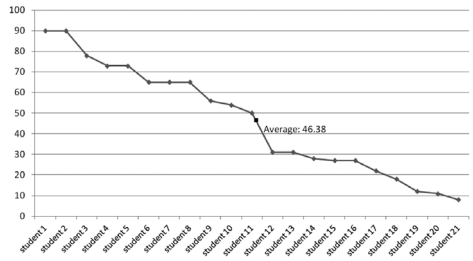

Figure 3. TTCT Creativity Index national percentile distributions among participants.

4.2. CORRELATIONS

TABLE 2. Correlation of TTCT, ASAT, Spatial Ability, and Studio Performance Grade

	Studio grade	TTCT CI	ASAT	Mental_R	Paper_P	Visual_V
Studio grade	1	.546	.011*	.466	.079	.365
TTCT CI		1	.548	.062	.526	.373
ASAT			1	.208	.423	.812
Mental_R				1	.021*	.015*
Paper_F					1	.037*
Visual_V						1

**Correlation is significant at the 0.01 level.

*Correlation is significant at the 0.05 level.

The scores of the TTCT, ASAT, three general spatial ability tests, and the studio grade were compared, using correlations. Table 2 shows that the ASAT and studio performance grade correlate at the statistically significant level; however, studio performance does not correlate with the TTCT or other general spatial ability test results. The ASAT does not correlate with all three general

spatial ability tests. Statistically significant correlations emerged among the three general spatial ability tests.

The ASAT consists of three different types of questions. The scores of each type were compared with the studio performance grade in order to judge which part of the ASAT correlates with the studio performance.

Results show that only Type A correlated with the studio performance grade at a statistically significant level (Table 3). In addition, type C did not correlate with Type A, Type B, or the ASAT, showing that the ability to reinterpret 2D information as 3D is the most significant ability in studio performance in architectural education (Type A). The ability to reinterpret from 3D as 2D may not be a significant ability in architectural education.

TABLE 3. Correlation of Three Different Categories of ASAT, General Spatial Ability, and Studio Performance Grade

	Studio grade	ASAT	Q1-5	Q6-10	Q11-15
Studio grade	1	.011*	.005**	.071	.678
ASAT		1	.000**	.000**	.021
Q1-5			1	.002**	.930
Q6-10				1	.562
Q11-15					1

**Correlation is significant at the 0.01 level.

*Correlation is significant at the 0.05 level.

5. Discussions

5.1. TTCT CREATIVITY AND STUDIO PERFORMANCE

Deviating from the assumption that creativity plays a significant role in architectural design performance, the TTCT score did not correlate with studio performance perhaps because the TTCT is based on the divergent thinking creativity that basically measure fluency and originality among many features of creativity. Creativity is a "multifaceted phenomenon" that is hard to define with one simple term (MacKinnon 1978, p. 46).

The failure of the studio performance grade to correlate with the TTCT indicates that a student's performing well in the design studio may not necessarily mean that she or he can generate many relevant ideas (fluency) or unconventional/unique ideas (originality) or vice versa. In addition, it does not necessarily mean that the student is good at abstract thinking (abstractness of titles), elaborating ideas (elaboration), or being open-minded (resistance to premature closure).

5.2. ASAT AND STUDIO PERFORMANCE EVALUATION CRITERIA

Because the ASAT correlates with studio performance, it is important to understand the evaluation criteria for studio performance. The criteria comprise four aspects: (a) independent development, (b) project comprehension, (c) evidence of reading and research, and (d) articulation of intentions in graphic, constructional, and verbal presentations (from syllabus, p. 3). The learning objectives for that studio are to develop understanding of technical graphic skills, 2D and 3D formal and spatial relationships, media presentation skills, and 20th-century modernism in architecture. Considering that the ASAT tends to test the ability to connect 2D and 3D images, which is the fundamental ability in architecture design and a training target during the beginning stage of architectural education, one must conclude that it is reasonable to have such corresponding results.

5.3. GENERAL SPATIAL ABILITY, ASAT AND STUDIO PERFORMANCE

Studio performance correlates with the ASAT but not with general spatial ability. In other words a student's performing well means that he or she is good at the ASAT but not necessarily at spatial visualisation or mental rotation. Why the studio performance does not correlate with the general spatial abilities is not yet clear. The architectural design process may involve so many aspects and abilities that neither mental rotation nor originality can cover.

Another possible reason is that the ASAT requires ability different from what other general spatial ability tests entail. In order to perform the ASAT task, students need a working memory to maintain information (Park et al. 2006). They also need to recall information to find a matching shape; furthermore, they need to transform 2D information into 3D or vice versa. In addition to the content difference, the format difference is that the ASAT provides questions and answers in sequence, not simultaneously, in order to avoid simple matching forms that might appear in the simultaneous format.

The other possible reason is that the ASAT requires domain-specific knowledge, such as reading floor plans or 3D drawings. Whether laypersons who do not have any background in architecture can perform well on the ASAT remains uncertain. In addition, if advanced students are tested with the ASAT and TTCT, the result might be different due to the different criteria for evaluating studio performance. Seeing how spatial ability and individual learning style are related would be interesting.

The finding of this paper is tentative and exploratory, yet it may promote interesting discussions and questions about how architectural spatial ability relates to design performance, what good studio performance means, what

abilities contribute to studio performance, and what creativity means in the architectural design domain.

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DESIGNING-IN PERFORMANCE THROUGH PARAMETERISATION, AUTOMATION, AND EVOLUTIONARY ALGORITHMS

'H.D.S. BEAGLE 1.0'

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Abstract. Design is both a goal oriented and decision making activity. It is ill-defined by nature as designing includes weighing and understanding trade-offs amongst soft and hard objectives or in other words vague or imprecise and computationally definable criteria and goals. In this regard designers in most contemporary practices face a crisis of sorts. How do we achieve performance or sustainability under these large degrees of uncertainty or with limited design cycle times? Fundamentally design collaborations, teams of domain experts, are not typically given enough time to design-explore, generate design alternatives in order to find or evolve solution quality through expansive design search spaces. Given these limitations of time and the ever more complex criteria for 'designing-in' performance our research approach provides a computational strategy to expand the solution space as well as pre-sort and qualify candidate designs. The research presents a novel methodology and technology framework and an initial implementation that was developed to enhance the human activity of design exploration, domain integration, and further evolve design process for performance goals. The research does so through generating and optimising a highly correlated solution space in conjunction with a near simultaneous evaluation of design alternative fitness.

Keywords. Parametric design; multi-disciplinary design optimisation (MDO); evolutionary algorithms; performative design process.

1. Introduction

The early design stage of any project can be considered the least constrained phase where design decision-making has the most significant impact on a project's ability to maximise its design objectives. Of particular importance to our research are the objectives for performance; aesthetic, energy and financial. In current practice, domain specific knowledge necessary to meet the requirements of individual objectives has been poorly integrated into an overall design process. Simulated performance feedback is often performed in an asynchronous fashion. This issue expands once coordination of different disciplines is taken into account and limitations of time and resource are considered. In this paper the development of a framework and technology that allows for rapid development of multi objective design problem solution spaces is presented. The use of an evolutionary approach is described, in which a genetic algorithm is used to both automate the design alternative population while facilitating multidisciplinary domain optimisation. This methodology specifically enables a generative process where performance criteria are integrated into the early stage model to improve upon design cycle latency and design uncertainty through visualised and analysed convergence of multiple design criteria. The paper provides a technical description of the performance based design methodology and platform design that integrates associative parametric models with an energy use intensity calculator and a financial pro forma. The initial results of the research are presented and analysed including noted impacts on the design process regarding design cycle latency and the affordances for designing in performance and managing design complexity. A summary discussion proceeds to explore the future of *design optioneering* based on our continuing development of the technology for a cloud-based implementation.

2. Precedents and background research

In contemporary practice, designers focus mostly on meeting the functional and programmatic performance criteria to satisfy the design requirements in early stages, while other performance criteria are deferred until a later phase (Turrin et al. 2011). Dealing only with narrow ranges of performance without quantitative criteria in the early phase decreases the quality of the final design solution (Chong et al. 2009). Generating expansive design solution spaces in early design stage is also absent from the typical architectural design process as designers mostly focus on small sets of alternative solutions (Turrin et al. 2011). However, repeatedly generating and evaluating design alternatives in the conceptual stage provides most satisfactory design solutions (Liu et al.

2003, Yi and Malkawi 2009). Generating alternative geometric configurations is a significant affordance of parametric modelling, and the number of tools and methods that support architectural design are increasing (Burry and Murray 1997, Hesselgren et al. 2007, Gerber 2009). Although generation of multiple design alternatives is a major advantage, the requirement of evaluating each alternative individually according to pre-set performance criteria arises. Furthermore the number of performance objectives increases both complexity and time necessary for the evaluation process (Flager et al. 2009). Integrating a set of performance criteria or parameters in early design process allows for multi-disciplinary design collaboration due to generation and performance evaluation being done simultaneously (Holzer et al. 2007). However, this also requires domain specific feedback from experts and their simulation tools in order to drive the design evolution. Traditional design entails manual adjustments to the design at hand after performance evaluation have been carried out by domain experts with no linking between geometry and engineering parameters (Sanguinetti et al. 2010). Researchers have identified this lack of dynamically linking simulation data to design models as an obstacle for performance based design (Oxman 2009). Automated generation and evaluation of design alternatives shortens the design cycle and enables design exploration (Grobman et al. 2009). In addition as satisfying design objectives is often an intrinsic trade-off between competing objectives, genetic algorithms (Frazer 1995) have been seen to offer potential solutions by facilitating search and ranking through expansive possible scenario sets (Wright et al. 2002).

3. 'H.D.S. BEAGLE 1.0'

In order to acquire and provide efficient feedback to support early design stage decision making, the development of a method and tool the *H.D.S. Beagle 1.0* was structured through three major activities: parameterisation, automation, and evolutionary algorithm.

3.1. H.D.S. BEAGLE 1.0: PARAMETERISATION METHOD

In order to automatically generate a solution space, it is necessary to first formally define the design problem regarding design objectives, variables, and constraints (Marks 1997). With regards to this research, design objectives are defined as the goals of the optimisation exercise. Constraints are defined as the criteria that a design option must satisfy in order to be considered a feasible design solution. Variables are defined as parameters of the design that can be manipulated for a defined range to achieve objectives and satisfy constraints. These definitions were then used to generate an associative parametric digital

model – in this case using Autodesk® Revit™ – that was driven by the design variables specified. The purpose was to provide designers a visual means of observing direct cause and effect of modifying variables on the resulting design configuration to ensure consistency with design intent. In accordance with the interest of the project, all necessary parameters were divided into three primary categories: design, energy settings, and financial pro forma.

Design Parameters: Design parameters are specified by the designer and are the driving factors of form and building massing. The geometric parameterisation process takes into consideration 1) Form driving parameters for design intent, 2) Site constraints parameters, and 3) Level setting parameters to vary level-to-level heights and assign space usage accordingly. Level setting parameters were discovered to be particularly critical as they enabled automated exploration of design program configurations.

Energy Setting Parameters: As the project utilises Autodesk® Revit™ to form the energy model, energy related parameters can be varied into two categories: 1) global energy settings (or project-wide setting); 2) individual energy settings associated with mass zones and mass surfaces. To form the energy model, Autodesk® Revit™ transforms a defined mass into an energy model with the following elements: Mass Exterior Wall, Mass Floor, Mass Glazing, Mass Interior Wall, Mass Opening, Mass Roof, Mass Skylight, Mass zone and Mass Shade. Each mass element provides properties that are related directly to expected energy consumption. Settings within the energy setting dialog box, or global energy settings, are applied to all the mass elements. Currently, *H.D.S. Beagle 1.0* utilises 13 global energy settings, along with enabling individual surface energy settings.

Financial Parameters: Parameters of the financial pro forma are based on a simplified financial calculation model that determines the net present value (NPV) of the design in question. The financial model and parameters used in *H.D.S. Beagle 1.0* can be separated into 4 sets: construction cost, operation cost, revenue and financing. With regards to the construction cost, 10 items were taken into account. The construction costs are designed to correlate the geometric model with its conceptual construction type. Conceptual operation costs are calculated based off of program areas combined with schematic energy costs provided by the energy analysis results from Autodesk® Green Building Studio. In terms of revenue, this is determined according to space usage and space program type. Relevant financial parameters were generated in a worksheet as part of the Excel template within *H.D.S. Beagle 1.0*. The values and NPV worksheet provides flexibility needed in order to calibrate the financial model to reflect market values and project specifics accordingly.

3.2. H.D.S. BEAGLE 1.0: AUTOMATION

After designers have defined the problem and objectives of a design project, a solution space is be automatically generated. To solve the current interoperability issues and automate the process, *H.D.S. Beagle 1.0* was developed using C# to be a plug-in for Autodesk® Revit™ to integrate three domains: design, energy and financial. The platforms integrated by this research include Autodesk® Revit™, Autodesk® Green Building Studio™ (GBS), and Microsoft® Excel™. Autodesk® Revit™ was used to provide the parametric modelling platform and geometric configuration engine. Autodesk® Green Building Studio™ is a web-based energy analysis service that served as the energy simulation engine. Microsoft® Excel™ provided not only a means of containing necessary financial parameters but also an interface to hold design parameter ranges, constraints, and formulas needed to calculate design scores. The automation loop of *H.D.S Beagle 1.0* was enabled by custom coding of the Revit and Excel API's and GBS SDK.

3.3. H.D.S. BEAGLE 1.0: EVOLUTIONARY ALGORITHM

One brute-force solution to parametric design is to traverse all possible combinations of all possible design variables in order to isolate optimal design solutions. However, such an approach is time prohibitive as design solutions exponentially increase with the number of variables explored. For example, 5 design parameters for an orthogonal building with 13 energy parameters, where each parameter only has a choice of 2 values has a potential number of $2^{(5+13)} = 262{,}144$ solutions. If each solution takes 1 minute to analyse, a full analysis of all solutions would require approximately 182 days to generate. Real design problems typically possess more than just 5 design parameters, and each parameter has larger ranges than 2. The use of Genetic Algorithm (GA) was employed as a means of providing a more efficient manner to intelligently search through and locate optimal results. Our GA optimises an initial set of individuals using three steps: 1) evaluation, 2) selection, and 3) population. During initialisation, quantities of dissimilar individual solutions are produced. The solutions are then evaluated based on a series of "fitness criteria" and selections are made by the programmed fitness function, which evaluate the rate how close the solution is to the optimal solution. The more "fit" a solution is, the higher the probability that the solution will be selected to "survive". The next step serves to propagate the population through a recombination of genes and mutation. This three-step process is then repeated, with each cycle representing one step of the evolutionary process, i.e., a new generation. The process is cyclical and therefore continuous until an optimal solution is gener-

ated or other stopping criteria are reached. In order to provide practical feasibility of GA within *H.D.S. Beagle 1.0*, the method and definition of some key components were defined as described below:

Encoding In GA, individual genotypes are often represented by binary strings. Each binary bit is considered as a gene, with the binary string being named a chromosome. However, this approach allows for "mutations" to occur which might allow the design to exceed previously defined constraints. Therefore, in order to ensure compliance with design constraints, the actual parameter value is used directly for each design variable instead of binary strings to represent the genes on the chromosome in GA. Such an encoding method is widely used to solve practical problems.

Fitness Criteria & Fitness Function In our research cases, three objective functions are used to evaluate offspring and determine "fitness" levels of individual offspring.

Objective Functions of *H.D.S. Beagle 1.0:*

D_{obj} = Max. DRCP

F_{obj} = Max. NPV

E_{obj} = Min. EUI

Where

D_{obj} = Design Objective Function

F_{obj} = Financial Objective Function

E_{obj} = Energy Objective Function

DRCP =Design Requirement Compliance Percentage

NPV = Net Present Value

EUI = Energy Use Intensity

Evaluation As design problems are a multi-objective optimisation problem (MOP) including multiple objective functions, the optimum becomes defined as locating solutions which compromise (trade-offs) rather than a single optimal (Coello Coello et al. 2007). Therefore, the Pareto optimum was selected as the optimisation method for this project. A specific Pareto front Ranking Method was adopted for our research.

Selection Our initial selection method was based on the fitness proportionate selection. In this selection method, the probability that each individual is selected is proportional to its perceived fitness in that generation, i.e. the individuals ranked highest are most likely to be selected than those ranked lower. However, this method may lead to early convergence by premature super individuals. To avoid this drawback, the tournament selection method was chosen instead (Miller and Goldberg 1995).

Population method Currently, the population method, crossover ratio, mutation rate, selection size, and maximum iteration number are set by the

user manually in H.D.S. Beagle 1.0 in order to accommodate for user preference and due to varying complexity and scale of design problems.

Convergent criteria In the current version of the *H.D.S. Beagle 1.0*, there are two mechanisms that will stop the GA; the first is defined by the user as the maximum iteration number when initialising the GA; the second is defined when the GA reaches three generations that have the same optimal result i.e. there no longer is a quantifiable improvement or difference. At this point the GA will determine that the design has reached the optimal solution.

4. Case study

In order to test the capabilities of *H.D.S. Beagle 1.0*, both real world design problems and hypothetical design scenarios were utilised. The case presented here was an example of a real world design problem adapted to *H.D.S. Beagle 1.0* and used to demonstrate the capabilities of the tool. The project used for this case study was provided by a design team, who is developing a high-performance K–12 school prototype building design with approximately 25,000 to 30,000 square feet of usable program space. The intention of this design was to generate a flexible and efficient prototype design that could be replicated and adapted to multiple sites. The design intent provided by the designer of this project expanded upon the requirements set forth by the client to achieve a net zero energy building configuration for each site using a flexible module created by the designer.

Original design Process – in house In the original design process a configuration of the adaptable module was generated for a specific site in an attempt to maximise the expected efficiency of the design. Once a design was generated then the configuration was analysed by creating an energy model in Autodesk® Revit®, and exporting the model into a gbXML format for Autodesk® Ecotect® and eQuest, for analysis. Once the analysis was obtained then the design was manually altered according to designer experience and another analysis was run in order to determine any measurable difference between the designs. However, this trial and error process was not efficient enough to provide relevant feedback in a timely manner. This is in part due to interoperability issues between the software used. This is also in part due to that even after the analysis was generated using the tools previously mentioned, there was not the ability to isolate direct cause and effect of design changes to the expected performance of each design.

Original design process with MEP consultant During the design process an MEP engineer was employed to assist in generating a more efficient design configuration using the adaptable module previously mentioned. The intent was that the MEP engineer would be able to provide a more efficient starting

point for the design and be able to aid in providing suggestions for optimising the design configuration's system efficiency. However, the result was that the MEP engineer was able to provide suggestions for optimising systems within a single design configuration and was unable to aid in the optimising of the design configuration itself. In addition, the analysis cycle for each design configuration required 1 week, thereby minimising the results of the analysis on the design configuration due to time constraints. This is in part due to the level of detail of the analysis provided by the MEP engineer for each configuration. While the in house analysis provided by Autodesk® Ecotect® and eQuest was a preliminary schematic analysis, the MEP engineer analysis was provided at the level necessary for generating final construction documents. Therefore, while the MEP analysis provided was more complete for each configuration, it was not efficient enough to provide relevant feedback in a timely manner to support decision making at the schematic design phase of this project.

H.D.S. Beagle 1.0 application The introduction of the Beagle here was used as a test to emulate the design process and determine if a notable improvement in the efficiency feedback loop could be observed. In order to utilise Beagle for this project the objective of the design and desired variables required explicit definition at the beginning of the process. At this point the designers defined maximised energy efficiency as the overall objective. The base geometry in this case is fixed, however, the glazing ratio, sill height of glazing, and depth of shading devices is variable for optimising for different sites. Figure 1 summarises the design parameters and the results of south facing wall. The Beagle ran 5 times with different site orientations of: 0, 22.5, 45, 67.5 and 90 degrees. *H.D.S. Beagle 1.0* successfully presented the optimal configurations for each orientation within 11 generations. The total time spent for each run was around 6 hours with 500 configurations analysed each time.

TABLE 1. Process Comparison.

	Initial Model #	Energy Result	Feedback time
Original: In house	1 for each analysis	1 result per run	1 day per analysis
Original: MEP consultant	1 for each analysis	1 result per run	1 week per analysis
H.D.S. Beagle 1.0	1 for all analysis	>800 results per run	800 per 8 hours

5. Results and conclusions

In our *H.D.S. Beagle 1.0* research we observed findings that so far demonstrate an improvement in the performance of generated design solutions within the context of this and other case studies. There has also been a significant observed reduction in design latency. *H.D.S. Beagle 1.0* allowed the designer to go from analysing one design per day to over 800 per day (see Table 1).

Given the exponential complexity of design problems the benefits from utilising this type of methodology are substantial. Comparing the three processes used during the case study, *H.D.S. Beagle 1.0* was able to provide relevant feedback in a timely manner in order to influence the schematic design phase of this project. Future work needed is to further investigate how to acclimate this process to accommodate early stage design. Of interest is the design process of translating design problems into formulaic parameters that can then be explored by *H.D.S. Beagle 1.0*. As a there are elements of design which are resistant such a translation, a full investigation of these elements is underway in order to maximise potential benefits or to more accurately gauge the relevance of *H.D.S. Beagle 1.0* to the design process. A second continuation of the research includes further development of the optimisation algorithm, data visualisation and designer interfaces.

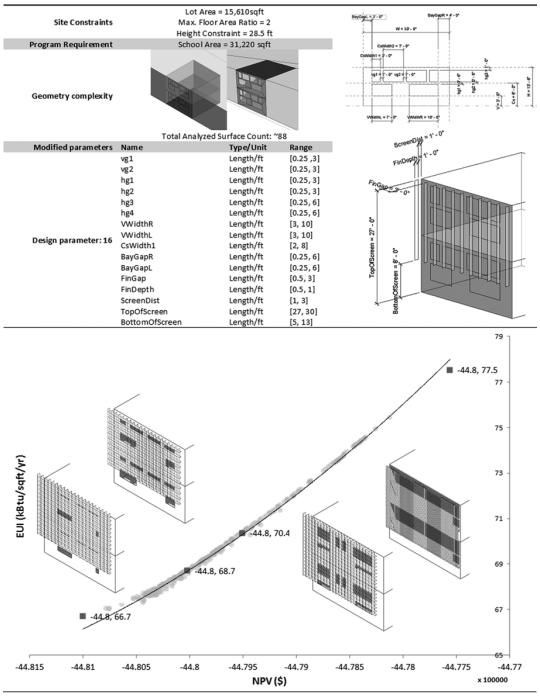

Figure 1. Analysis result summary.

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DIAGRAMMING IN A DIGITAL ENVIRONMENT

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Abstract. Research into digital design environments has explored modelling, generating and testing design propositions. When considering the broader design literature, however, we notice that a significant contribution to design is absent, that of diagramming. In the realm of architectural theory discourse in the past few years, diagramming has been much discussed with many interpretations of the activity. This paper will demonstrate that the development of digital techniques can change dramatically our ability to conceptualise and produce generative diagrams as previously not possible. The paper will follow the work done at the in the Melbourne School of Design. We will demonstrate how students are introduced to diagramming techniques and shown how to formulate a concept, then a program generator and to test a final proposal. The paper will also demonstrate how digital techniques can dramatically change the way we conceptualise and approach design problems. In this repeated teaching technique, we illustrate how digital systems contribute to conceptual diagrams and this contributes to the larger theoretical debate on diagramming techniques by introducing digital perspectives. The paper will therefore contribute to discussion on the ways in which digital systems can be engaged in substantive architectural teaching beyond the rote application of proprietary software and representative approaches.

Keywords. Diagramming; parametric; design; urbanism; abstraction.

1. Diagrams and the design process

Although the fundamental importance of diagrams and representations has been examined and understood across disciplines (for example, Latour 1986), our exploration of the potential and contribution of diagrams in architectural design (Herr and Karakiewicz 2007, Karakiewicz and Kvan 2010) has recently been reinvigorated (Garcia 2010). In this edited collection, for example, Spuy-

broek (2010) writes that diagramming is one of the most important innovations in architecture during the past 15 years.

The current understanding of diagrams in design can be observed to emerge through the past half century; in 1966, Christopher Alexander described diagrams as "any pattern, which by being abstracted from real situation conveys the physical influence of certain demands or forces" (Alexander 1966). Scholars, such as Lawson concluded his research on the design process by stating that architects and designers "finding it hard to think without a pencil in their hand" (Lawson 1994, p. 141). Fraser and Henmi (1994) describe diagrams as a self-conscious reductive process, pointing out that diagrams have an important feature to exclude a lot of irrelevant information. The examples given are abstractions of movement, noise, shadows that maybe symbolised in order to represent intangible information and to focus on their relevance to the design context. Although almost all chapters in Garcia (2010) limit themselves to description and representation, the potential is far greater. For example, Schön (1992) wrote persuasively about architects using sketching and diagramming to enable conversations with the object that is being designed.

Designers use diagrams to test and develop their intentions and concepts or to convey complex information. Design ideas that we explore in our cognitive capacities need to be externalised and tested in order that substantive progress can be made through structural reinterpretation (Verstijnen et al. 1998); in this, diagrams play an affordance role as condensers of our visions. Diagrams not only influence how we think about design processes but also how we communicate them to ourselves and others, thus influencing profoundly what we understand of our own conceptual ideas (Kraut et al. 2003, Heiser et al. 2004).

We sketch and diagram when we want to involve others with our design processes (Tovey et al. 2003). Diagramming amplifies our capacities through communication to bring others into the design process, engaging a collective capacity to design. Typically, we use diagrams in the initial stages of design: in the restaurant when we draw on napkins, on the train, on the back of envelope (Lawson 1980, Robbins 1994).In these discussions, diagrams and other non-scalar representations are abstractions that play significant roles because they allow for reinterpretation that open up the conversation to emergence and discovery (Goel 1995, Schön and Wiggins 1992). It is the qualities of abstraction and non-representational imagery of diagrams that enables this kind of engagement.

And if we were to describe the process of design as of making the new, at the design stage "the new" is only the projection, or an extension of what is already there, and therefore not that new at all. However by abstraction of

essence, or meaning, of what we are trying to achieve, we are often able to get rid of our preconception and be able to perceive "the new" (Boden 1992).

2. Digital diagrams

The work of Bill Mitchell traces the transition of our approaches to computer aided design from a computationally driven prescription through to a means to understand design outcomes. As Mitchell (2001) notes in *Vitruvius Redux* he made a fundamental shift in his thinking since writing *Vitruvius Computatus* (Mitchell 1975), a transition from a generative approach to computational design through to a renunciation of this in recognition that the potential of the computational lies in an interpretive. In the latter, the logical and procedural are opportunities for reconceptualising the theories of architecture by removing representational and semantic constraints of design processes. Thus, computer aided architectural design moves from prescription to potential.

The computer has not replaced the pencil as means of exploration although the end was declared (Mitchell 1989). It has long been recognised that computer-aided design systems, whether for architectural applications or otherwise, fail to support conceptual exploration through their focus on literal representation by means of geometrically specific data (Lonsway 2002, Meniru et al. 2003).

In addressing this shortcoming, a variety of approaches have been taken. For example, Gross (1996) sought to allow sketching to facilitate references to precedents as part of the exploration of possible form, a matter of graphical search rather than conceptual development. The failure of CAAD to simulate design processes similar to that involving the back of the envelope, or napkin lies not only in the representational form of the computer images which look too perfect, unlike the ill formed and evocative bleeding pen lines on absorbent napkin which invite contribution. Nor is the failure the result of technical accessibility to such digital environments – with current tablets and sketch apps, only a blunt figure is needed and, as the increasing number of iPad-based exhibitions of art and imagery testify, creative graphical images can be achieved (Hockney 2011).

As with many such apps, such systems are context bounded in their applications. For example, the Dynamic Engine (Autodesk Maya) is equipped with a solver to address complex networks of both forces acting on objects and objects interacting that diagrams complex outcomes in relatively simple form. Constrained to a particular realm of data types and output forms, the system facilitates certain conversations.

While these sketches are trapped in their system constraints, there are side benefits of sketching in the digital environment. We are able to share and

develop our designs intents in even more extensive ways today by posting our diagrams on line and asking for contribution by others. Time and explorative capacity are expanded as diagrams travel around the world (Hirschberg et al. 1999).

Fundamentally problematic, these 'tools' are not exploratory devices. "Computer-aided design representations have for the most part ignored this progression from abstract and low-commitment diagrams to detailed, specific and higher-commitment drawings." (Gross 1996). It is still difficult to have the same conversation on-screen that we can have over the napkin in the restaurant, or on the back of an envelope. Our proposition is not that the systems are inappropriate to this conversation but that we could engage with them in a different manner. To do so, however, we need to consider how we might use the opportunities particular to such an environment.

While diagrams and sketches are often thought of in a graphical manner, it is clear that such conceptual explorations occur in other representational modes and that the transfer of concept from one mode to another plays a powerful role (Kvan et al. 2003). In this aspect too, apps and task specific tools fail in their support of this conceptual activity.

In recent years, though, a palette of choices have emerged that offer a context for developing diagrams for design. In parametric systems, we have identified an opportunity to reconsider the way in which we create diagrams through representations in graphical, data and analogue representations, thus extending diagrams to encompass cognitive activity beyond the pencil and napkin.

Parametric diagrams can manipulate more variables that we can visualise in our heads. Interactive diagrams of sun and shadows can test our proposal and inform us of the implications of our data decision and even suggest what we need to change. Parametric diagrams powerfully engage complex data arrays and permit a range of manipulations of such data outside system assumptions that allow us to *diagram* without lineation. In doing so, however, we contend that it is important to retain the potential of diagrams and how they can be employed. In the following sections, we will describe our engagements in a teaching context with parametric diagrams.

3. Teaching parametric diagramming techniques

For the past 15 years we have been using diagram in our studios at the University of Hong Kong (1995–2008) and at the University of Melbourne (2008–2012). The non-representational quality of the diagram was the main interest in these early studios, reinforced by an engagement in data and algorithm as a means of manipulation.

Initially we used abstraction as a form of diagramming that freed students of their preconceptions reinforced by traditional precedent focussed studio teaching and expanded potentiality. Commonly used as a teaching strategy, this encounters skill constraints immediately. When asked to create an abstract painting to develop concepts for the site or illustrate the essence of the site conditions, students were only as successful their artistic talents permitted.

We progressed to another form of diagram, that through metaphor. Metaphors are used to help students to express the difficult unknown through that which they know (Lakoff and Johnson 2003). The advantage of the metaphor was that it does not establish a relationship immediately; it permits reinterpretation and allows imagination to develop in more than one direction. Metaphors are also successful in multiple forms, whether graphical, linguistic or numeric. In this, they lend themselves to parametric interpretation. As Jencks (2010) observes of what he calls *semantic space*:

> …when meaning is concerned, it is the relationships that count. Why? Because the mind, language and reality operate in a hyperspace of multiple dimensions, of countless relationships, not just in a well-laid-out supermarket, with all the aisles clearly marked.

We started by using CATIA Digital Project software as part of the studio and diagramming techniques for Urban Design in 2004. Used at this time only for specific descriptive representation of building form as a BIM system, we were keen that students use Digital Project not to create a final alluring object but to use it as a device to represent a conceptual process; therefore, we were very specific that our students should only use Digital Project to develop *diagrams* that developed design intentions.

Importantly, this process required students to distance themselves from literal translations of digital diagrams into formal architectural propositions.

One student used Gamelan Music as a metaphor to create a program generator (Figure 1). The notation of gamelan music was adapted by replacing different instruments in the orchestra with urban functions. The notation of each instrument was analysed to make sure that the relationships between values are semantically correct. The musical script was then translated to a site specific context (Figure 2).

From the functional mix composed by the Gamelan generator, possible structural and formal responses were explored. Importantly, the translation is not literal – the functional mix is not a formal composition.

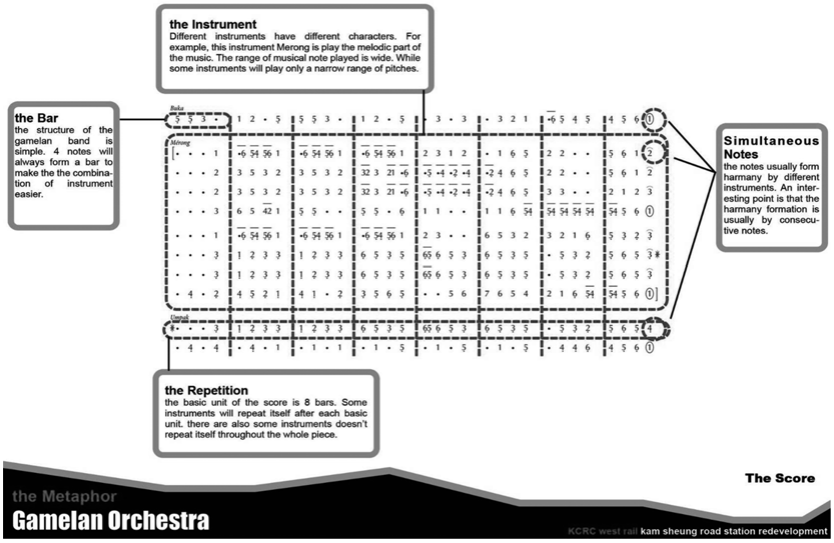

Figure 1. Gamelan Music as a metaphor for program generator.

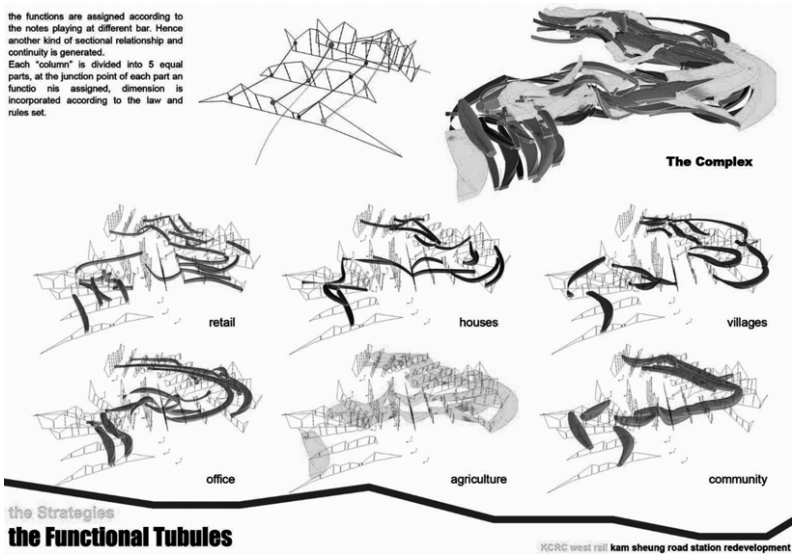

Figure 2. Output from the Gamelan Music program generator.

In another example (Figure 3), the diagram explored the permissible plot ratio and possible functional mix based on parametric modelling of required

sun hours for different functions within the plot ratio boundaries. In this instance, the models for sun penetration in winter, summer and spring engaged with assigning the floor plates to functions which could be accommodated based on the sun hours delivered during winter time.

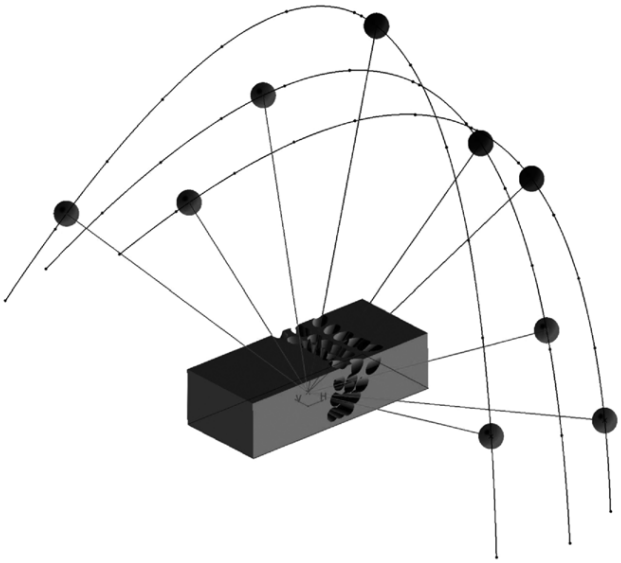

Figure 3. Sun path diagram, executed as a subtractive exploration of form.

3.1. DIAGRAMMING EMOTIONS

In 2010, another series of diagrams started to appear in our studio. Those based on emotions, exploring how emotional sensitivity might play a role in our perception of our environment. In this, the students explored the significant role of emotional reaction to the way in which we experience our environment.

Students recorded smells, noises and textures. Smell was particularly interesting since it related to desire to encounter a pleasant smelling object and the reactions it provokes, such as consumption. The weeks spent on collecting data, resulted in series of stimulating diagrams; students used Rhino to visualise data reflecting the emotional reactions on site as reported by sample populations taken across demographic groups that included participants from different backgrounds, cultures, age groups and sexes. Students used the same diagramming techniques to represent all the different senses and these diagrams became the starting point for designing interventions within the city structure.

3.2. TRANSLATING DIAGRAMS

Diagrams can be useful in representing complex, intangible data that cannot be easily visualised. Because these diagrams are often seductive, however, they can be very easily understood as a final product of form even if they are specifically called diagrams. Students find it difficult to move past literal translations of the diagram to form to understanding that diagramming techniques could be used as program generators or starting points of the design processes where intentions or relationships are first established. In this, the studio that involved diagramming emotions was particularly interesting. Emotional diagrams cannot be easily mistaken for built form but translating these type of diagrams is even more difficult that translating diagrams of wind or sun movement.

To illustrate the potential we will refer to a project that stood out, that by Shima Gafouri. Gafouri took water as an element, which could provoke all the emotions diagrammed previously. Reading and interpreting the messages hidden in emotional diagrams, she was able to construct a proposal where emotion could be amplified or suppressed, depending on time or by controlling points to enhance a location that previously had little to offer.

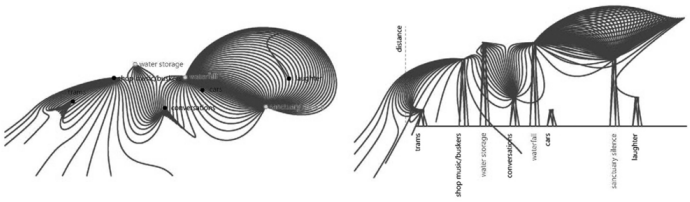

Figure 4: Water as an emotion (Shima Gafouri)

4. Discussion

We are in early stages of understanding the potentials of parametric diagrams and the many aspects of their creation and application have not yet been fully explored. As we have experienced with other representational forms, it will take time to engage sufficiently that we can move past a perception of these as limited to data manipulation. As it is with the mastery of drawing, music or dance, the immediate mechanical engagements initially overwhelm the interpretation of outcomes. It is apparent, however, from these teaching experiences that the potential is there in parametric representations to develop a language of diagramming.

What distinguishes this approach is that the design activity proceeds from a digital representation of a design idea – digital in that the idea is represented

directly by data i.e. numbers. This numeric description is then examined through graphical diagrams which may then be extended into an object representation. Manipulation of the data transforms the diagram and the object; design is therefore carried through an understanding the significance of the data themselves.

In this approach, the digital realm is employed to deconstruct our preconceptions of form as a design response. Initially, this is done by removing the design situation from its common frame of formal response. By disturbing the cognitive approach through a change of framing, we re-perceive the context of the design opportunity.

Typically, design perception privileges those aspects of a situation understood to be relevant, important or useful, but the measures by which we determine such attributes are grounded in our preconceptions or in precedents. We are therefore typically unaware of the frames in which we respond to a new situation. In studio teaching through a data-driven design response, we require new framing to be explored.

Diagramming is central to this approach. As explained above (Jencks 2010), metaphorical diagramming allows the relationships of component parts to become the focus. Thus, as students diagram emotions, experiences or understanding, they can depict through data a new perception and review this in a diagram before progressing to a formal proposition. In studio discussions, the conversation moves back and forth between classes of data deployed, particulars of these data, the diagramming technique chosen and the knowledge revealed by these choices.

Studio critique then steps away from an immersion in form and object to the generators of these outcomes. Peer discussions are observed to be conducted in the language of particularities of a design opportunity and the generalisation of such specifics to architectural knowledge. The parametric is no longer then a stylisticism but a structure in which to reveal design strategy.

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CUSTOM DIGITAL WORKFLOWS

A new framework for design analysis integration

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Abstract. Flexible information exchange is critical to successful design integration, but current top-down, standards-based and model-oriented strategies impose restrictions that are contradictory to this flexibility. In this paper we present a bottom-up, user-controlled and process-oriented approach to linking design and analysis applications that is more responsive to the varied needs of designers and design teams. Drawing on research into scientific workflows, we present a framework for integration that capitalises on advances in cloud computing to connect discrete tools via flexible and distributed process networks. Adopting a services-oriented system architecture, we propose a web-based platform that enables data, semantics and models to be shared on the fly. We discuss potential challenges and opportunities for the development thereof as a flexible, visual, collaborative, scalable and open system.

Keywords. Visual dataflow modelling; design processes; interoperability; simulation integration; cloud-based systems.

1. Introduction

There is a clear and urgent need for better information exchange strategies to address the persistent lack of interoperability and integration in building design, analysis and construction. Recognising that most design teams use a variety of software applications and platforms, the question that remains to be answered is: How can we develop tools and technology that support designers in creating their own design processes, rather than having to adapt their processes to suit the tools' rigid requirements?

The key idea we present in this paper is that bottom-up, user-controlled and process-oriented approaches to linking design and analysis applications are more appropriate than current top-down, standards-based and model-oriented strategies, because they provide degrees of flexibility critical to the process(es) of design. This idea comes from discussions raised at the "Open Systems and Methods for Collaborative BEM (Building Environment Modelling" workshop held at the CAAD Futures 2011 Conference in Liège, Belgium, early in July 2011. Here, we continue the 'open systems' dialogue with a conceptual framework for bringing this idea into practical application, aiming to reduce current obstructions to collaborative design. We propose an open framework for integration where numerous small and specialised procedural tools are developed, adapted and linked ad-hoc, to meet the needs of individual design projects and project teams. These modular components encapsulate individual tasks that aid information exchange between domain-specific software by (semi-) automating typically tedious and non value-adding tasks associated with matching and mapping data across different schemas. A cloud-based platform enables project- and user-specific workflows to be created, shared and managed on distributed resources, via web interfaces that allow users to interact with workflows graphically. This, in combination with the elimination of file format and mapping language restrictions, ensures maximum flexibility.

Drawing on research into scientific workflows, we describe system requirements to guide future development of the proposed framework. We present a system that dispenses with an ontological premise for integration, and discuss the benefits and challenges that such a system presents for design practice and outcomes. Although no implementation of the framework has yet been created or tested, we are in the process of assembling a team of researchers and practitioners interested in pursuing our proposal. We are confident that the approach described in this framework will lend itself well to coping with the frequently

changing pace and focus of design projects, as well as the varying priorities of their many stakeholders.

2. System architecture

Similar to the AEC industry, increasing complexity in scientific research and practice has led to a proliferation of specialised computational tools, each developed by different people, at different times, to support different problem-solving tasks. Across these tools, underlying data structures exhibit a high degree of heterogeneity, akin to that observed in building software. To manage this heterogeneity, and achieve the integration required to generate solutions, information must be matched and mapped across a succession of different schemas, applications and platforms (Bellahsene et al. 2011). Scientific workflows enable these information exchanges to take place quickly, reliably and flexibly, by "combining data and processes into a configurable, structured set of steps that implement semi-automated computational solutions of a scientific problem" (Altıntaş 2011, pp.9-10).

Scientific workflow systems enable the composition and execution of these complex task sequences on distributed computing resources (Deelman et al. 2009). These systems exhibit a common reference architecture, illustrated in Figure 1, and typically consist of a graphical user interface (GUI) for authoring workflows (which can also be edited textually), along with a workflow engine that handles invocation of the applications required to run the solution (Curcin and Ghanem 2008). The workflow engine supports integration between applications by engaging a combination of data-flow and control-flow constructs to handle the execution and management of tasks. Data-flow constructs establish information dependencies between tasks, and ensure that data-producing procedures are complete before data-consuming ones begin (Deelman et al. 2009). Control-flow constructs support more complex workflow interactions, such as loops and conditionals, and also coordinate the execution of tasks on remote resources (Deelman et al. 2009). Typically, control-flow constructs are overlays on the data-flow graph, either as separate nodes or layers.

Today, numerous workflow systems with different purposes and functionality exist. Some provide sophisticated interfaces and graphics, like the data visualisation application Vistrails (Callahan et al. 2006), while other more generic workflow systems, such as YAWL, are less visual but offer high-level process abstractions that can be applied to a range of usage scenarios (Curcin and Ghanem 2008). The LONI Pipeline is designed specifically to build up data processing streams for neuroimaging tools (Rex et al. 2003), while Kepler provides advanced control algorithms for actor-oriented modelling of complex physical, biological and chemical processes (Curcin and Ghanem 2008). Each

system acts to accelerate and streamline the problem-solving process, however, individual capabilities vary greatly due to differences in workflow representation, data flow and control flow.

Implementation strategies for each of these three aspects of workflow are the product of specific requirements and technologies needed for the individual field or purpose for which a system is developed. In the following subsections we discuss strategies for workflow representation, data flow and control flow in relation to the needs of the AEC industry, aiming to capitalise on recent advances in cloud computing.

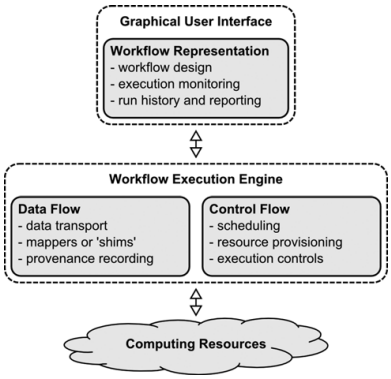

Figure 1. Workflow system architecture.

2.1. WORKFLOW REPRESENTATION

Workflow representation is critical for specifying tasks and dependencies. Nearly all workflow systems mentioned are visual programming tools in that they allow processes to be described graphically using some form of 'pipes-and-filters' logic. While not strictly workflow systems, programs like Grasshopper and GenerativeComponents abstract underlying CAD systems to offer similar functionality to designers for composing parametric-associative models. Each 'filter' encapsulates some data processing task, represented by a node, while a 'pipe' passes data (and in some instances control information) between two filters, represented by a connecting wire. A workflow is depicted by a network of nodes and wires to be configured and reconfigured graphically by users as required. From a user perspective, these nodes can act as a black box to perform a given function without the need for extensive or expert programming, although programming can empower the end user considerably.

Adopting this 'pipes-and-filters' architecture, our framework posits three node types: process, input/output (IO) and control. Process nodes encapsulate data analysis and transformation procedures; while the latter two node types provide functionality related to workflow initiation, execution and completion.

Process nodes have a number of (typed) input and output ports for receiving and transmitting data, as well as variables that can be set by the user to guide task execution. They can be further classified into tool nodes and mapper nodes. Tool nodes wrap existing applications to make their data and function-

ality accessible to the workflow, while mapper nodes apply transformation procedures to data sets to map the output from one tool node to the input of another. Figure 2 shows an example network in which a Maya modelling node is connected via a series of mapper nodes (denoted by 'M') to EnergyPlus and Radiance simulation nodes. The Maya node encapsulates a procedure that starts Maya, loads a specified model, and then generates a model instance by applying the defined parameter values. The resulting geometric output undergoes two separate transformations that map it into both EnergyPlus and Radiance compatible formats. The simulation nodes then read in this transformed data, run their respective simulations, and generate output data in the form of simulation results.

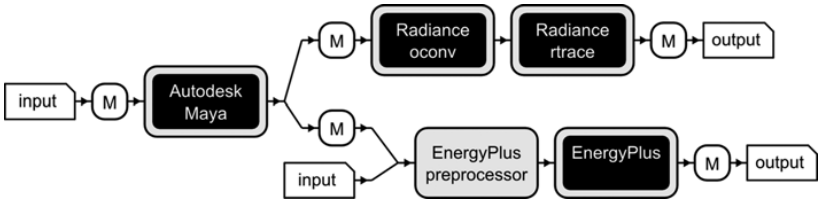

Figure 2. Exemplar workflow.

IO nodes act as data sources and sinks for the workflow. Input nodes provide the data by specifying input files and control parameters as inputs to the tool nodes and to control the data extracted from these input files. Taking the example in Figure 2, the Maya input node allows the user to specify not only the model to be used for the data source, but also particular types of geometry contained within it, while the EnergyPlus input node might simply link the appropriate weather file. Output nodes contain the workflow results, here of the EnergyPlus and Radiance simulations. They can be linked to a number of visualisation tools to display results, and users are able to define data 'mashups' in order to customise their visualisations without having to understand the coding of the underlying processes.

Control nodes apply constraints to the workflow, like conditionals and loops, which manipulate the local order of execution of nodes further along in the network. For example, an *if–then* node can force execution of different branches in a workflow, while a *repeat* node can force repeated execution of a network branch. Global control is also possible, but is defined at workflow level, rather than task level, as discussed in Section 2.3.

Users configure nodes and their dependencies using a workflow interface. Since we are describing a platform that operates in the cloud, this interface would be a web application able to access distributed cloud services.

We propose a HTML5-based GUI that provides drag-and-drop functionality for placing nodes on the workflow canvas, which are then wired together by the user, similar to defining a model in Grasshopper. We also propose interface functionality to aid users in managing workflow complexity. Graphical nesting allows clusters of nodes to be collapsed into composite nodes, facilitating modularisation of the workflow to improve its legibility (Davis et al. 2011). Provenance information retrieval and querying enables workflow history to be reviewed, so that the decision-making process can be tracked (Deelman et al. 2009).

2.2. DATA FLOW

Interoperability is a critical issue when linking applications from different domains. Scientific workflow systems deal with this in a number of ways, ranging from an ontological approach, where a common file format is imposed on data exchanges, to an open-world approach, where the user resolves data format issues as needed - a process known as 'shimming' (Altıntaş 2011). In the AEC industry, the prevailing solution to this issue is Building Information Modelling (BIM), which tends toward the all-encompassing ontological end of the spectrum. This is a top-down approach, reliant on the IFC data model and its continuous extension to cater for all possible usage scenarios. Pragmatic information exchange is assumed to evolve into process-oriented model views, where only filtered subsets of the model are exchanged (Eastman et al. 2011).

Rather than reading and writing to a common representational structure, we propose tools be coupled more effectively through procedures that allow direct data transfer, as advocated by building simulationists (Hensen et al. 2004), and transfer only needed data, rather than entire models (Augenbroe et al. 2003). While this approach is vulnerable to version changes in wrapped tools, the sharing and reuse of interoperability solutions would be a mitigating factor. Furthermore, the proposed system does not disregard BIM, but suggests IFC exchange be part of the workflow process, integrated into these custom data flows rather than forcing the whole system to adhere to its ontology. A good example of such an approach is found in the "GeometryGym" suite of tools, which enable parametric models generated in Grasshopper to be linked both to BIM workflows, through components that generate IFC objects, and to structural simulations (Mirtschin 2011).

Considering all data to be exchanged as files, we may allow any other data formats next to IFC, such as CAD data in the form of DXF, IGES or comparable proprietary formats, XML formatted data or other structured data or text, or even plain text. This list is deliberately open-ended; while the absence of any format restrictions may complicate the exchange of data amongst numerous

tools, it avoids significant limitations of both an ontology-specific data representation (such as IFC) and a domain-independent general-purpose data format. Choosing the latter would undoubtedly result in situations where translations from highly customised data representations to the general-purpose format and back pose significant risks of information loss. The only necessary restriction that we envision is that data formats are identified and their assumptions described, such that any mapper node may reasonably rely on these assumptions when reading in data. This restriction does not limit flexibility concerning data formats, as a new format may always be identified and described.

The selection of files as the medium for data exchange is prompted as much by the elimination of any data format restrictions as by the choice of a cloud-based platform. However, the use of distributed data files over a centralised data model may introduce data redundancy and inconsistency; e.g. when different workflow branches drawing on the same input converge, combining data from different but overlapping models. Such redundancy, admittedly, is inherent to the bottom-up approach to integration that we are advocating. Eliminating this redundancy, however, would not only greatly reduce the freedom and flexibility of designers to create their own workflow processes from any selection of tools, it would also seriously hamper the ability to define and explore unconventional design spaces.

2.3. CONTROL FLOW

As discussed in Section 2.1, control nodes provide localised ways of manipulating the workflow. To provide the desired level of flexibility, the framework also needs to offer different types of global control flow. Many existing workflow systems are restricted to simple flow mechanisms that generate topological orderings, where each node will execute only after all its predecessor nodes have executed. A key limitation of this approach, however, is that the network must be a directed acyclic graph (DAG), so networks with loops are not supported. Networks with loops, however, are clearly desirable in certain situations, such as optimisation procedures. To support loops and other node execution patterns, such as triggering nodes iteratively or periodically, different high-level control mechanisms are required. In addition to providing workflow execution functionality, these mechanisms are needed to support distributed computing, by triggering nodes to work in parallel with other nodes, as well as executing synchronously or asynchronously. To ensure maximum flexibility, the user should be able to apply different control flow mechanisms to different parts of the network. This could be achieved by assigning a control mechanism to a composite node, which would further open the possibility of nesting control flow.

3. System implementation

Implementing our framework in the cloud ensures its scalability, efficiency and reliability, as node execution can be distributed over multiple computers in the network. Process nodes are therefore defined so that both their data and procedure can reside in the cloud. Input and output data is saved in files, and a (distributed) repository is used to manage these files. The node procedure is saved as an executable task (which may be written in any language) that reads and writes files, and a task scheduler is used to manage the execution of these tasks in the cloud.

Files resulting from one process node may be stored local to the execution of the node's task, awaiting retrieval by other process nodes. Storing files ensures a trace of all workflow output is maintained for later perusal. Files may also be copied to different locations and their copies managed within the repository. Similar to version-control systems, local file copies in combination with a local copy of the repository guarantees access to all outputs even when the user is disconnected from the cloud. File management within a repository also eliminates the need for exchanging files directly between process tasks. When a task creates output files, it registers their location (URL) together with some minimal metadata – origin, time of creation, format, etc. – for which the Dublin Core (http://dublincore.org), extended where necessary, may serve as a template. In return, it receives tokens corresponding to the various files (typically unique IDs assigned by the repository), which are passed to the task scheduler to be forwarded on to the next process node's task. The receiving task then queries the repository for the metadata and the file(s).

4. Discussion

The question of interoperability has been vexing the AEC industry for decades. The usual response is to impose standards for data formatting and construct monolithic design-analysis systems that internalise, and thus opaquely subsume, representation problems. This inflicts severe limitations on the ways in which information, and therefore designs themselves, can be described. To overcome these limitations, we are proposing that the bugaboo of BIM research and development – communication that is direct between domain-specific applications rather than via a common standard – is the preferred and even necessary arrangement. Although more work may be needed to create the multitude of possible data converters required to support such communication, this is better than over-constraint of the design process caused by the use of standardised representations and processes that are only applicable within a relatively small region of 'design space'.

Research and development of the proposed system is an ongoing effort from the Open Systems group, however, success will ultimately depend on a community of users and developers, able and willing to create, share and maintain process nodes to support various design and analysis activities. This could potentially result in a vast collection of process nodes and an endless range of options. To aid the designer in choosing appropriately, it is important not only that a description of the functionality of each node is available, but also that the designer is able to ensure that nodes 'fit' other nodes in order to compose a valid workflow. Assertions must therefore be specified on node outputs and assumptions specified for expected inputs so that automatic checking of node compatibility is possible.

Workflow design is likely to be an incremental process in which a number of nodes are combined into a partial workflow, tested by the designer, and then further developed and extended. Besides automatic checking of the mutual fitness of adjacent nodes, the designer will need to check whether the (partial) workflow is behaving as expected and producing appropriate results. When the results are not as expected, the designer will need to debug the workflow by tracing back execution, which can be assisted by displaying intermediate, as well final, results. In the context of a vast collection of process nodes and choice of alternative ways to achieve the same or similar result, user-friendliness and knowledge-based support, the two main concerns of designers when using analysis software (Attia et al. 2009), will become crucial. Issues of accuracy, uncertainty and risk may also be of significant concern. Macdonald et al. (1999) propose the introduction of uncertainty considerations in simulations to provide meaningful feedback to the user and to improve confidence through risk assessment. While these should be addressed within individual software tools, the proposed system should also introduce this functionality into the workflow environment itself.

5. Conclusion

This paper represents an ongoing effort to address limitations in process and technology that presently obstruct design collaboration. In it we argued the need for a user-controlled and process-oriented approach to integration and interoperability, and discussed how a cloud-based workflow system can support more flexible and distributed design processes. We examined the features and functionality needed to abstract computing and data resources to make tools and technologies more accessible to users, both as individuals and as members of design teams. As well as benefiting design practice, we envisage the proposed system as a platform for researchers to share their work and increase the impact of their individual efforts through integration with other

research. The system requirements that we have established will ensure that the proposed integration platform is developed to be flexible, visual, collaborative, scalable and open.

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HOW SOCIAL IS THE VIRTUAL DESIGN STUDIO?

A case study of a third year design studio

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Abstract. With the advent of social networks, it became apparent that the social aspect of designing and learning plays a crucial role in students' education. Technologies and skills are the base on which learners interact. The ease of communication, leadership opportunity, democratic interaction, teamwork, and the sense of community are some of the aspects that are now in the centre of design interaction. The paper examines Virtual Design Studios (VDS) that used media-rich platforms and analyses the influence the social aspect plays in solving all problems on the sample of a design studio at Deakin University. It studies the effectiveness of the generated social intelligence and explores the facilitation of students' self-directed learning. Hereby the paper studies the construction of knowledge via social interaction and how blended learning environments foster motivation and information exchange. It presents its finding based on VDS that were held over the past three years.

Keywords. VDS; SNVDS; social intelligence; design education; social learning; problem-based learning.

1. The evolution of the Virtual Design Studio at Deakin University

Since 2000 at Deakin University, a selection of design studios have been founded initially on online project submissions, assessment and the generation of virtual galleries of student work (Ham and Dawson 2004). Over the

next years, this digitally supported design studio evolved by using *YouTube* in project submissions and student-authored online blogs as reflective portfolios (Ham 2010). With greater emphasis on computational aspects in design generation, communication and learning the studio evolved further into blended learning environments that intersect conventional studio culture with elements of Virtual Design Studios (VDS) that have been established over the past twenty years (Kvan 2001). The latest studio form that integrates online social networking aspects as the key element of design communication and interaction, called the *Social Networked Virtual Design Studio* (SNVDS), is operating since 2009 (Schnabel and Ham 2012).

In 2009 the studio used as online Learning Management System (LMS) the (at that time freeware) *Ning*-platform {www.ning.com}. This social network platform that works outside of the standard Deakin University LMS, Deakin Studies Online (DSO), was chosen due its ease of use, multimedia applications, social networking capabilities, and two-way communication functions. Since 2010 however, Facebook (FB) {www.facebook.com} replaces Ning as LMS due to its higher social acceptance and usage among students. Alongside conventional and recorded video-lectures, face to face and video studio tutorials, on- and offline learning resources, and other VDS elements the design studio engaged learners in blended learning environments that made use of the online social networks of students, educators and the internet community. This evolution over the past decade has seen a transition of a design studio from its conventional and traditional base to its current state of a blended SNVDS.

2. The social networked design studio

The design studio presented here is the capstone experience for the undergraduate architectural degree, where students must demonstrate their prerequisite skills and knowledge for entry into the Master Degree programme. The third year Bachelor programme at Deakin University operates on campus with an enrolment of 178 students. The cohort comprises 140 students studying a Bachelor of Design, 36 students enrolled in a double degree of Bachelor of Design and Bachelor of Construction Management, and 2 students in other categories.

The SNVDS was a nine-week design studio based on an international online competition issued by *[AC-CA]* (Architectural Competition - Concours d'Architecture) {http://ac-ca.org}. The competition, the 'Hong Kong Alternative Car Park Tower' (HKACT) was framed as a mini-thesis that would *'test students' abilities in design within a context that will operate outside way of their comfort zone'* (project outline). The competition brief was as follows (AC-CA, 2011):

> The aim of this International competition is to design an iconic and Alternative Car Park Tower in Hong Kong Central. […] The architecture of this new building should reflect contemporary design tendencies, standing out for its uniqueness as a car park design, while meshing in with the surrounding Hong Kong urban tissue

The site of the competition provided the ideal vehicle to pursue SNVDS methodology, providing opportunities to engage in design in an international context, development of cultural understandings, address issues of sustainability, study climatic conditions and other design relevant issues that related to the high-density urban setting of Hong Kong. Students and tutors utilised online resources for design decision support, including Google Maps, webpages, Skype, email, FB, and assistance from 'virtual studio tutors' remotely located in Australia, Hong Kong and China connected with the students via various internet communication tools. These online-resources and -tutors are blended with a diversity of information sourced (face-to-face) in lectures and studio sessions. The SNVDS was framed, supported and enabled using a FB-group {http://www.facebook.com/groups/237519682933398/} as LMS as described in Schnabel and Ham (2011).

3. Engagement in the SNVDS

The SNVDS was evaluated in October 2011 through an online survey of students enrolled in the studio. The survey aimed to provide both qualitative and quantitative responses to gather a broad body of complementary information to support the research "in which the considerations that qualitative researchers raise, and the questions about worth and intent posed by philosophy, are as much a part of the discussion as are measurement and analysis" (Sherman and Webb 1990). Sixty-seven students (37% of the cohort) self-selected and completed the survey via a link from the FB group.

3.1. STAGES OF ENGAGEMENT

The qualitative analysis of the students' survey can be grouped into three phases of students' engagements with the LMS, each stage lasting around one third of the studio time, namely *induction, socialisation,* and *maturity*.

3.1.1. Induction

The initial phase of *induction* involved the introduction of the SNVDS concept to the cohort, the lecturer demonstrating the group's potential and modes of engagement being outlined. This introduction is usually met with some apprehensiveness from the cohort, as one student commented:

> I initially questioned the use of Facebook, it seemed to be playing up to a fad to try and make the students excited about design in a different way.

3.1.2. Socialisation

Once students learnt that FB offers them a potential value in learning, they received more relevant and informative information via the LMS. This marks the beginning of the second stage, the *socialisation*. Here, students were socialised into the academic use of FB (outside of their own online social environment) and started to gain increasingly more some value from the social network. Previous assumptions are challenged; however, full engagement was still limited. Using social networks in a learning environment that not only serves socialisation needs, but also a learning source needs time to establish trust, connections and content.

3.1.3. Maturity

The third stage of *maturity* is when the students become familiar with the modes of engagement and the value of the group and actively participate in a mature manner, contributing to the group according to their own requirements. One student describes this staged engagement in the FB group:

> I first thought it was a bit unusual to use Facebook as a study medium, however as people started to post up questions and work it was really useful as I would check Facebook more often than I would DSO and as a result was more easily exposed to answers and discussions."

3.2. ANALYSIS OF THE LMS

Although everyone in the cohort joined the FB group and had access to wall posts, links and other information, levels of engagement varied over the trimester and according to individual learning styles, motivations and needs. Survey data revealed that 88% of respondents logged into the FB site at least once a week. From this sample, 38% logged in passively to read posts made by others, with 12% accessed the group to actively read and write posts. 38% contributed further by initiating and responding to student discussions. Engagement in the FB group, as evidenced by the number and type of posts increased as the trimester progressed. A sample of participation in the FB group was taken in week seven of the HKACP project with modes of engagement from each participating student identified and tabulated. From the cohort of 178 students, 53 students actively participated in the group by initiating posts and links, commenting on posts and links made by others and 'liking' posts and links made by others. 129 students did not participate or were passive participants, limiting

their engagement to reading comments and posts made by others. This engagement is illustrated by one respondent's comment that "I did not post any information but found reading through other's posts to be of assistance."

The studio coordinator was the most active participant in the group during the survey period. His contribution totalled 54, including ten comments, 40 replies to student or own comments, three links to websites, one reply to a post and one 'like'. The Hong Kong-based virtual studio tutor, who initiated three posts relevant to the project, provided additional valuable feedback to support the students' learning. The cohort included a group of 10–15 highly active users. One student initiated nine posts (asking questions clarifying the project), making 28 comments and another student making six comments (images of his work for feedback) and 28 other comments.

The SNVDS environment is as much a function of the personalities involved as the technology. Online presence and interactions differ from face to face, because hierarchies, thresholds and etiquettes are not the same (Barkhuus and Tashiro 2010). Sometimes people took on a self-appointed role online, which sometimes received a reaction from other students: "only 1 thing bothering, there is a student, acting like he's the 2nd moderator of SRD364 FB page."

3.3. NOMADIC DEVICE GENERATION

University students are often noted as early adopters of technology, 'since they are young and in the process of becoming well educated and since many universities were pioneers in the use of computing, often opening up access to all students' (Barkhuus and Tashiro 2010). Architecture students in this cohort are approaching a state of 'nomadic ubiquity' (Attali 2011), where optical fibre, Wi-Fi, 3G and 4G mobile technologies are used in conjunction with a range of nomadic devices such as smartphones, tablets and laptop computers. Online sources such as FB, *MySpace, Twitter, Skype* and the various *Google Apps* enable unprecedented connectivity. . It is this connectivity that has unlocked many of the learning outcomes of the SNVDS, which has parallels with how the first VDS unlocked the potential of digital media in design learning (Kvan and Kvan 1999).

FB is ubiquitous amongst the cohort, with 176 from 178 students having a FB account at the start of trimester and 81% of respondents accessing FB more than once per day. 48% of survey respondents used their laptop to engage in the FB-group, 24% their smartphone and 25% a desktop computer at home. A combination of these devices enables multiple modes of access from the home, in transit and in the design studio itself. This convenience of access and accessibility to the "Nomadic Device Generation", as we called it, was widely received by students as positive. This is reflected in one student's comment:

> The ability to share work and gain immediate feedback (although not utilised by all) was brilliant. It made the studio a 24/7 event, not just 4 hours on a Thursday afternoon.

The issue of access to tutors is critical in a design studio with 178 students, eight tutors and one coordinator and a weekly two hours lecture and three hours of studio contact times. The studio evaluations of earlier studios have consistently highlighted the lack of quality contact-times with tutors. The SNVDS offers an extension of the design studio outside of the limitations of scheduled classes, which is seen by some to fit in with students 'work hours' and nomadic lifestyles – as a student puts it – with its "ability to wake me up in the night (if I wished it to) is a far better communication platform, able to be delivered straight to my pocket".

Clearly, there is great potential for further engagement in nomadic technologies in design education. With almost ubiquitous student access to online learning resources, LMS, various forms of mobile and cloud computing, technology has matured to facilitate a blended learning environment that intersects various physical and virtual realms as well as social and cultural elements.

3.4. FACILITATING SOCIAL ENGAGEMENT

Barkhuus and Tashiro (2010) found that students' use of FB facilitated a variety of student-to-student interactions, including 'casual interaction online, leading to casual interaction offline'. In our case, this was extended to include both student-to-student and student-to-staff on- and offline interactions. . The informality of the LMS made it easier for some to seek information from the online community:

> Firstly, we can know and communicate to each other better even when we don't know them from the first time (sic). Then, it's a better way to ask questions as people might feel panic when talking in front of many students.

For some, this informal online learning environment was dominated by 'chatter', which distracted from the core learning tasks. One student thought the FB group was "intrusive and unprofessional" whilst another "I don't agree using social media for school projects, and I was quite displeased about being forced to do this." Despite these negative responses being marginal and limited to only a few respondents, it is important to note that a social network as LMS does not fit every learner's need and style, since the LMS relies on the social abilities of students. Social skills and the ability to interact socially becomes by default a necessary skill that learners have to acquire or have as prerequisite. This is manifested in the responses of the survey, in which the students indicate that their perceptions of the FB group changed over time.

Initial negative or neutral attitude, such as "I thought that everyone would not treat it seriously and just fill it up with rubbish" changed once socialisation, mature use, and richer learning content posted by group members brought about more meaningful levels of engagement:

> Initially I wasn't too excited as I was used to the DSO discussion thread however now I find it a very great way to communicate at a fast-pace which has been great with SRD [the FB-group]. Especially due to it being a design subject, sharing documents and photos has been much easier.

One constant issue of studio education is attendance at lectures and studio sessions. Attendance of face-to-face lectures fell from 80% in the first week to around 30% in the last lecture. Reasons for non-attendance, as outlined by Shannon (2006) generally include perceptions of marginal outcomes from lectures in students' busy lives, personal reasons and university workloads. Several survey respondents thought that the FB group contributed to poor attendance, with one student stating that "I felt it meant less people turned up to studio as everyone just use FB. I prefer one-on-one interaction with others than over the internet."

It is proposed that FB acted as a source of engagement in the studio to compensate for students, who perhaps would not have attended anyway. The FB group enables the design studio cohort, with its constituent blend of deep and surface learners- and students, who strategically transition from deep to surface, various modes of engagement that suit different learning styles (Saljo 1979). As Oblinger and Oblinger (2005) note, the *Network Generation* uses a variety of channels to learn. Face to face is only one of many others that learners use to build up their knowledge.

The SNVDS was widely perceived to have increased social engagement in the studio: "It was good to be in contact with other students, when usually we would not talk that much. It is easier to open dialogue with other students via FB." This was perceived to be of considerable value for some.

This increased social engagement contributed to 80.1% of respondents reporting that the SNVDS contributed to their learning of design. From this group, 38.1% reported a substantial positive impact on their learning of design. Moderated unit results demonstrated these outcomes across the cohort, with 8% High Distinctions, 27% Distinctions, 37% Credits, 17% Pass and 9% Fail (of which 6% were attributable to late withdrawals).

3.5. FROM COLLECTIVE TO SOCIAL INTELLIGENCE

Collective intelligence in architectural design invites anyone to contribute to a design process through crowd sourcing even if each of the design proc-

esses is individual. This is especially true in the SNVDS that employed Web 2.0 technologies to encourage everyone to contribute to a process – despite its competitive nature. As Paulini et al. (2011) state, developing successful collective design starts by understanding how individual and collaborative design are supported with computing technology and then goes beyond collaborative design to structure and organise the design tasks so that students are motivated to participate and contribute by gaining more value for their own design proposal. The LMS enabled many passive students to become participants: engaging in discussion forums, creating their own social and knowledge networks, taking part in polls and building communities and portals of knowledge. This provide opportunities for information to be shared among social groups, extending beyond the conventional studio setting, allowing for opportunities for collective intelligence to rise, and enabled through the social networks, the next step along the social and collaborative interaction, in which knowledge is generated and collected lies the *collective social intelligence.*

The key attribute of the SNVDS is the generation of a social intelligence that relates to both the current design project as well as knowledge in the relevant fields. The SNVDS differs from traditional model of delivery in that the students themselves became the primary contributor to skills, content, and knowledge required for the design project. It also differs from conventional problem-based learning (PBL) due to the difference of scaffolding and problem framing (Schnabel and Howe 2012). The ill-defined nature of the competition brief plays a crucial role in the development of the design proposal. The SNVDS not only framed the problem differently (Kvan and Gao 2004), but also engaged the students through the means of social learning resulting in a collective social intelligence that enabled learners to generate a wide diversity of responses. The tutor-to-student engagement evolved quickly into student-to-student engagement: "As the trimester progressed, I saw that questions were being asked and answered for all to see, that immediate responses could be given, and that discussion between peers slowly took over peer-to-lecturer discussion."

3.6. FLAT HEIRARCHIES

In 1993, Alison King predicted that future educators must undertake the transition from being 'the sage on the stage to the guide on the side' (King 1993). The SNVDS successfully negotiates this transition by flattening the hierarchical structure of the design studio where practitioners provide feedback to students based on their command of knowledge and expertise in design. In the SNVDS, the LMS flattened this hierarchical structure, since every member

has the same role and power to facilitated learning. The competition brief aided in this process, by specifically seeking for the development of a novel typology that has no precedent and is an architectural alternative to the conventional solutions. Students themselves thus became important sources of information that was shared with their peers. Tutors became learners too and the social and learning interaction on- and offline shifted from teacher-led to student-led. The amount of shared information is a key attribute to the social intelligence, resulting in "a positive increase (in learning) because lecturer used FB to share information 10x more than any has ever used DSO." One student reported that the FB group "felt more 'alive' and interactive", whilst another felt that "it was definitely a better experience – seeing posts and the encouragement of instant conversation."

This flat and democratic learning environment created "much more discussion and thought pattern among students. There was a greater dialogue between peers and teachers overall." Students themselves established a number of their own separate FB-groups, following the inspiration of the SNVDS: "Several students and myself created a group of our own for another unit... it's so much easier than emails etc."

In the due course of the studio, the flat hierarchy was maintained throughout all aspects of the studio including desk-critiques and final presentations. Tutors, local or remote, shared the discussions with the students as initiator and listeners and using the smartphones, LMS and Skype as real-time discussion contributors, rather than conventional expert-led jury deliberations.

4. How social is the SNVDS?

The collective social intelligence that aided and facilitated the students learning resulted in successful design proposals that addressed the needs of the different learning and design styles, and educational goals. At the end of the studio, students and tutors selected six design proposals for submission to the competition resulting in one student winning an Honourable Mention {http://www.ac-ca.org/en/hongkong02mentions}.

In summary, employing social networks in a blended learning environment responds to the need of learners to not only acquiring knowledge or solving ill-defined problems but also engaging in a social setting that generates collective social intelligence and flow (Schnabel and Howe 2012). The Nomadic Device Generation engages with knowledge and information differently, as the anonymous quote states: "If the news is that important, it will find me." This is only possible if one connected with networks that not only engage socially but also intelligently. This engagement is one of the fundamental pillars since the early VDS that "allows students to work collectively with colleagues from

different cultures and climates who are thousands of kilometres and in different time zones" (Bradford et al. 1994).

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RUNNING INTERFERENCE: COMPLEX SYSTEMS INTERVENTION AS DESIGN PROCESS

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Abstract. This paper presents a case study problem statement tested in the design studio with the intent of teaching methods for engaging systematic thinking as a process for deriving solutions to parametric design problems. The intent is to address the simulation environment developed through complex systems and interject a curve ball, or unexpected constraint delimiting the solution as part of the design process. This method was tested through the submittal of the projects to international design competitions. The students were asked to manipulate the competition criteria by appealing not only to the design criteria but also to the juries desire (whether conscious or unconscious) for novel sustainable processes of material usage and program. This material ecology is developed as a method for linking parametric modelling, not as a process for the application of a construction technique, but as a way to pre-rationalise material constraints and discover how program and form can operate within those constraints. In the first year of the studio two of six teams were selected as finalists and in the second year of the studio five of seven of the teams were selected as finalists.

Keywords. Studio pedagogy; computational instruction; parametrics; material constraints.

1. Introduction

As response to post-great recession expectations and as a natural arc of the evolution of design process, designers are in the midst of a struggle for clearer control over the parametric relationships, which govern our design process. There is undoubtedly a new pragmatism formulated through more meaningful responses to process fostered by the excess and flippant use of digital manufacturing equipment and the incredible flexibility of design software. There is

a clear desire to explore how design process is being redefined by complexity through software. The question remains how can the machine give us new solutions to problems we didn't even know existed, and how can it allow us to redefine the processes we use to assemble building components? This new functionalism has been a long time coming, though it is much more broadly accepted in times like these. However, the delimitation of process has been accelerated by the wide use of parametric software, providing more flexibility with every new software update. As a response to this apparent trajectory, this paper will demonstrate a design process and problem statements intended to develop students skills for systems based thinking, helping them re-shape their own design process to respond to computational design and complex systems. These problem statements define a method for investigating the layers of design process by impregnating the process with a foreign agent, capable of delimiting the design proposal through detail and materiality. The intent of these projects is to provide students with the ability to not just work with computation, but to understand how computational process can delimit outcomes, and how it can provide solutions through refinement of function (whether social, material, economic, or political).

As far back as 1993, Pallasmaa (1993) was recognising (and arguing for) a new "eco-functionalism" derived through the parameterisation of technology, materiality and form.

> Today...I cannot imagine any other desirable view of the future than an ecologically adapted form of life where architecture returns to early Functionalists ideals derived from biology. Architecture will again take root in its cultural and regional soil. This architecture could be called Ecological Functionalism... this view implies a paradoxical task for architecture. It must become more primitive in terms of meeting the most fundamental human needs with an economy of expression and mediating man's relationship with the world...and more sophisticated in the sense of adapting to the cyclic systems of nature in terms of both matter and energy. Ecological architecture also implies a view of building more as a process than a product. And it suggests a new awareness in terms of recycling and responsibility exceeding the scope of life. It also seems that the architect's role between the polarities of craft and art has be redefined... After decades of affluence and abundance, architecture is likely to return to the aesthetics of necessity in which elements of metaphorical expression and practical craft fuse into each other again; utility and beauty again united. (Pallasmaa 1993)

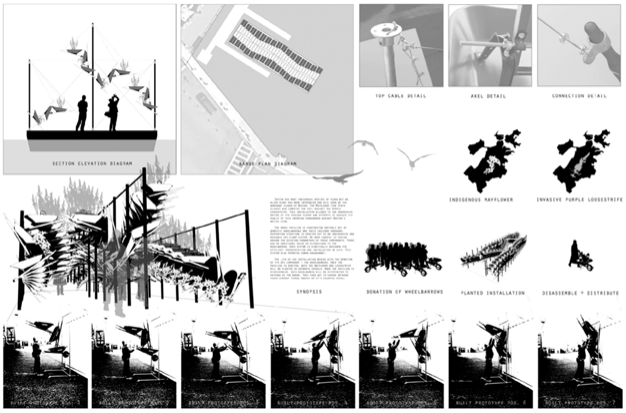

Figure 1. Shift Boston Barge2011 finalist competition submittal using wheelbarrows as primary construction system.

Few would doubt the growing importance of computational methods and thinking within architectural design, but what remains unclear is how a discipline such as ours can *become* computational. How do we arrive at the point of integration, when architects understand that computation is not just a tool, but a method for design? When all designers, not only specialists, can practice computationally and ruminate on the subject? Our goal is to trace possible trajectories and delineate obstacles on the way to making computation not the exception but a normative part of our methodology. The success of this transformation rests on something greater than the adoption of a particular level of vocational skill. It requires a cultural shift. As education is one of the primary instruments of implementing disciplinary culture, we must work to instil alternative values, attitudes, and beliefs regarding design through our studio pedagogy.

2. Systems for interfering

Parametric processes have broadened to encompass a variety of relationships between form and space: through inventive use of the algorithm to develop indeterminate forms, through parametric controls linked to material constraints, through political parameters as they relate to the identity of a form, through New Structuralism or the linking of parametric forms to their structural composition, or as a map of the social identity of place. In each instance there is an ethical question about the humanistic value of each process. How in the end do these relationships create the phenomenological experience good design is capable of providing?

The kind of systematic thinking or evidence-based design that Pallasmaa was called for takes on the kind of complexity, beyond the scope of most designers capabilities. These type of systems are defined as "complex systems" by mathematicians and computer scientists searching for a method to address and investigate layered relationships. Typically these involve simulations no human would be capable of solving, or simulations, which are emulating human activities. For design process, we require the foresight necessary to compose a design, properly engaging all of the necessary systems for both ethical and inventive solutions. The closest that we can attempt to come through conventional means is an idea proposed by Carpo (2011), would be through the use of collective intelligence. Rather than relying on a select system defined by particular invested parties, whom often have political or economical motivations, we ought to rely on a system of competing parties, arguing for best practices at that point in time, and for that location.

As a response to this question, we developed a design studio problem statement, proposing a methodology, which emulates this functionalist or logical approach. This requires first that the students have a baseline problem, in this case a carefully chosen international design competition. A design problem for a temporary installation functions best, for reasons outlined below. The two studios outlined in this case study used competitions for TOGS3 (Temporary Outdoor Gallery) Competition sponsored by the Austin Arts Alliance (2010), and the Barge 2011 Competition, sponsored by ShiftBoston. The baseline for this design process is the program and competition statement for each of these competitions. The programmatic definitions, as with most competitions, are quite varied and rarely offer much in the way of constraint. The temporal nature of each of these competitions provides more flexibility in the use of unconventional materials, both recycled or what we call pre-cycled (the purchase or donation of a new product which can be donated once the project is disassembled). By entering competitions the students are made to consider the client as someone who can be influenced by the tertiary layers of the design proposal, the layers which may not have direct effect on the form of the project, but which carry cultural or societal significance for the place or purpose of the project.

3. The secret agent

As an essential part of the design process, on the first day of the studio each pair of students is assigned an off the shelf recycled or pre-cycled component. Each of these materials allows the students the ability to argue that there is very little actual new consumption occurring on behalf of their design proposal. These material agents have varied including, wheelbarrows, 24′ 2″ ×

4″ trusses, traffic cones, 55 gallon steel drums, tires, radio flyer wagons. The objective of the material agent is to force the students to engage with a seemingly overwhelming amount of constraint. The fact that they are required to use an off-the-shelf unit, often devoid of architectural typology or precedent requires that they develop a truly novel method constrained by a material parameter.

Through the development of this architectural system, they learn how to use digital manufacturing equipment in responsible ways, minimising customisation while maximising form. These tests are developed through a variety of ways, at first simply by disassembling their unit, and exploring how it can be reassembled into other more spatial ways. Then through a series of both physical and digital models, using the constraints of the system to determine how a form could be applied at the scale of the competition program, or more specifically at the scale of the human body. Each iteration must be described in section to examine how the human body can safely inhabit the structure but also must be designed for disassembly, so that the original unit can be reused in a more conventional manner.

The process of designing for disassembly is crucial to our pedagogical perspective on the teaching of performance-based architecture as defined by more than the simple building product. It is composed of a complex set of systems, both technological and cultural, made of physical commodities and human effort. Ultimately, the designer is responsible for coordinating this discourse; responsible from the point of conception to the destruction of the building. This responsibility includes not only how the building performs throughout its life- cycle, but equally how it performs during construction, through adaptive re-use and in its eventual demolition. We must consider every commodity consumed in the production of building products as a part of its design. The EPA (2009) reports 331 million tons of construction and demolition waste and debris was generated in 2008. 60% of all landfill waste is a result of the building industry (not including waste from civil projects such as bridges, roads, subways, or rail systems.)

> We need buildings which fulfil their task today and will do so tomorrow, which in other words, do not age in adhering to their forms and this becomes a drag upon the economy as well as the visual environment. But in order to build adaptably we must try to build as lightly, as movably, as possible and with the greatest perfection technically available. (Larsen et al. 2003)

Each assembly is presented in the competition submittal with the intent of appealing not only to the design sensibility of the jury, but also to other more existential desires. As Pallasmaa (1993) argued the ecological system can (and

should) be motivated by political awareness. These can be political, social or ecological agents, but that each needs to be tangible, not metaphorical. In most instances, the materials were either recycled or pre-cycled (as defined earlier). We attempted to minimise (and make a big point of it) any new consumption for the sake of temporary construction. The material components, also come loaded with an identity not typically associated with design. We use this identity to relate to other publicly supported entities. These entities can be anything from an endangered species to a local non-profit. For instance, the wheelbarrow installation proposal for the *Barge2011 Competition*, was filled with the endangered Mayflower, the State flower of Massachusetts. Alternatively, the proposal constructed of 24′ trusses would be deconstructed and donated to a local chapter of *Habitat for Humanity*.

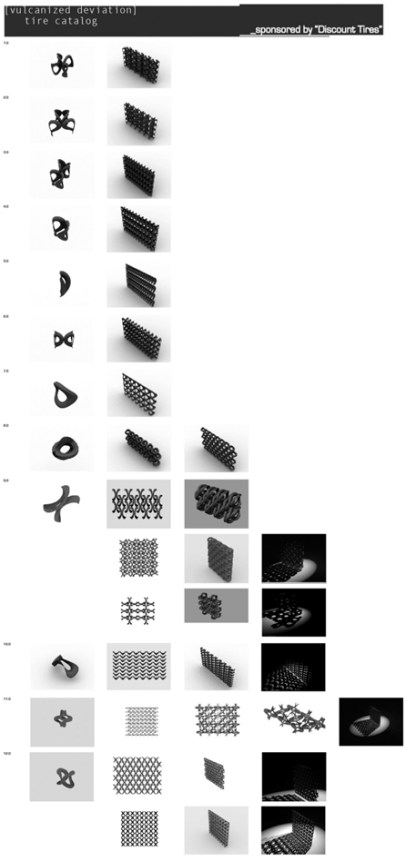

Figure 2. Iterations of sliced reused radial tire systems for the TOGS3 Competition.

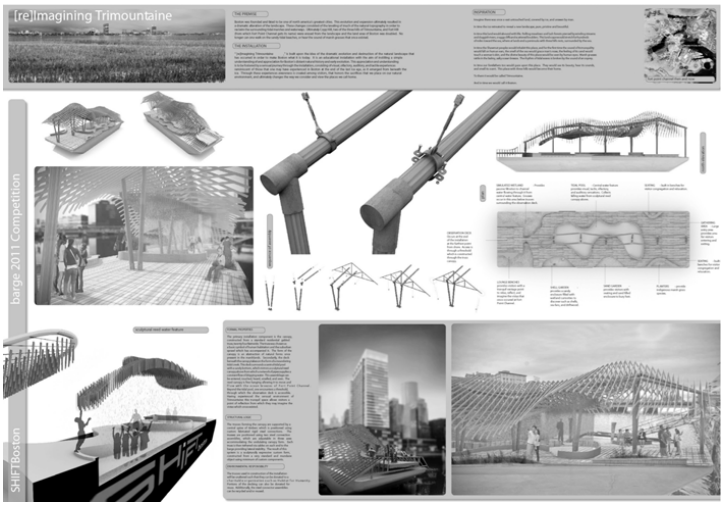

Figure 3. Shift Boston Finalist Competition Submittal using 24' gable trusses as primary construction system.

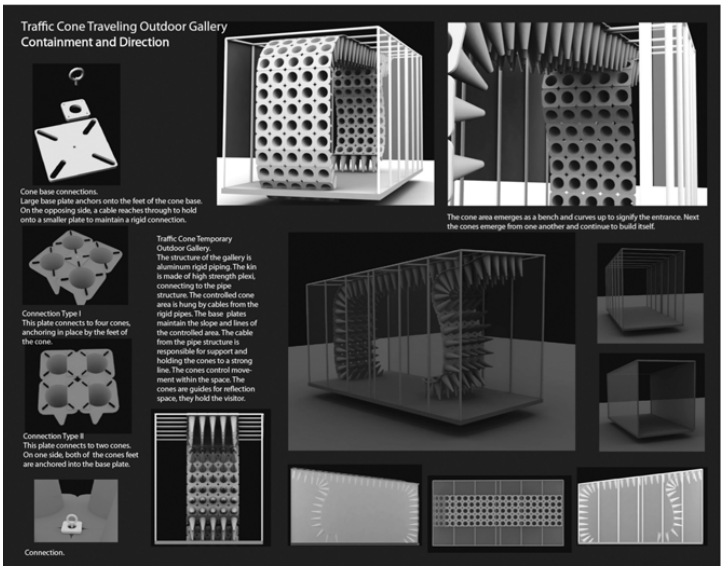

Figure 4. TOGS3 (Temporary Outdoor Gallery) Finalist Competition Submittal using traffic cones.

Our social goals for the project statement were focused on maintaining human usability and insuring that the identity of the original object was maintained.

The identity of the object can be used as iconography for the program of the facility and can/should draw attention from a public whom might be more prone to recognise an interesting use of traffic cone over a compelling conventional architectural detail, or even a highly customised digitally manufactured one. The haptic use of the material agent as a piece of furniture where the public is more likely to touch and manipulate it creates an environment where the users have the experience of place more substantially embedded in their memory. This can occur both through tangible connections but also through programmatic ones. The other finalist for the *TOGS Competition* used 6″ cylindrical ductwork (again to be donated to Habitat) to create a sound based installation where voices would be transmitted through the wall cavities to other locations on the installation, creating an interactive and layered experience.

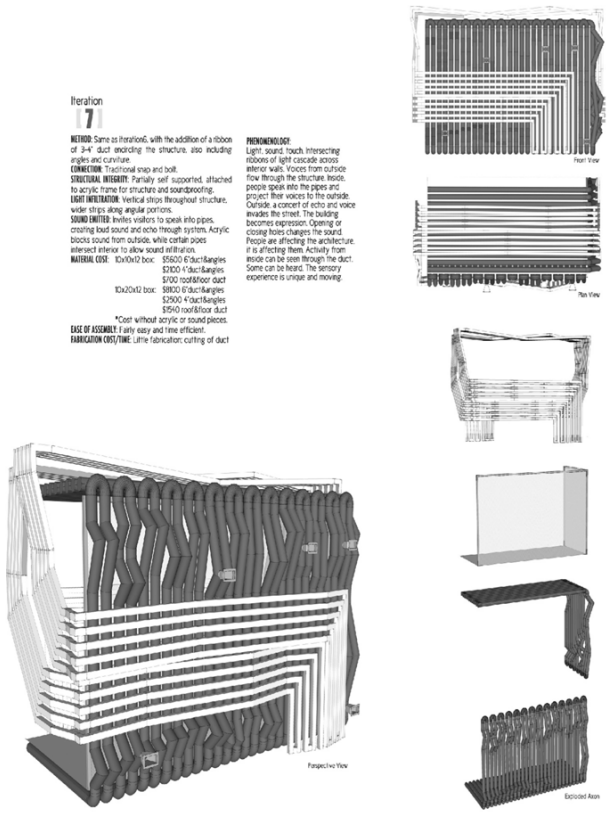

Figure 5. TOGS3 (Temporary Outdoor Gallery) Finalist Competition Submittal using duct work to create auditory connections through the walls of the installation.

4. Conclusion

The design problem outlined here creates a culture of creativity in the studio, which considers all parts of cultural life as valuable and integrated systems for logic and evidence based design. Computational discourse is clearly manipulating the methods that we use to design and construct. This type of thinking ought to be linked to ideologies with more meaningful connections to our experience, than most of the flippant aesthetically motivated design we see today. Our intent with these proposals is to demonstrate a process whereby computational thinking can afford the designer the ability to create their own parametric relationships, through more meaningful connections to materiality, consumption, political and social identities and evidence based ecological awareness.

The competitions for these case studies had nationally and internationally recognised jury members. Of the six projects submitted to the TOGS3 Competition two were selected as finalists and of the seven projects submitted to the BARGE2011 Competition five were selected as finalists. By the nature of recognition these projects create invaluable experience for students to understand the importance for creating a meta-narrative for their own design methodology. More importantly it gives them the experience to consider how parametric thinking can connect form to something more than a shopping list, but can reconnect us to what we do well, make design for people.

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DATA SHARING FOR SUSTAINABLE ASSESSMENTS

Using functional databases for interoperating multiple building information structures

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Abstract. This paper presents the development and implementation of an automatic sustainable assessment prototype using functional databases. For the practical purpose, we use Leadership in Energy and Environmental Design (LEED) as the exemplar standard to demonstrate the integrative process from building information aggregation to final evaluation. We start with a Building Information model, and use Construction Operations Building Information Exchange (COBie) as a bridge to integrate LEED requirements. At present, the process of sustainable building assessment requires information exchange from various building professionals. However, there is no procedure to manage, or use, information pertaining to sustainability. In our research, we translate rules from LEED into computable formulas and develop a prototype application to produce templates for LEED submission.

Keywords. Building information databases; sustainable assessment.

1. Introduction

In the building industry, assessment schemas are increasingly being used to objectively measure sustainability achievements. These are also known as ‘green/sustainability’ rating systems. A green/sustainable building rating system is defined as a tool that examines the performance or expected per-

formance of a 'whole building' and translates that into an overall assessment that allows for comparison against other buildings (Fowler and Rauch 2006). In the US, a commercial green building is generally considered to be one certified by a sustainable building rating system; for example Leadership in Energy and Environmental Design (LEED), which is developed by US Green Building Council (USGBC) to establish a common standard of measurement and evaluation (Yudelson 2008). Green building evaluation is a multi-person and multi-phase process (Turkaslan-Bulbul 2006); therefore, sharing building design information among different building domains and professionals is essential. The current process of sustainable building evaluation is highly disparate. Even with the use of conventional Computer-Aided Design (CAD) tools, this requires a great deal of human intervention and interpretation. This makes the process of sustainability assessment costly and time consuming. (Nguyen et al. 2010)

Keysar and Pearce (2007) have identified 275 tools in 14 categories, which are required, at various times, in evaluating sustainable buildings. To enhance cooperation and use of building information for assessment, we focus our research on current building information interoperability tools and standards in the Architecture Engineering, and Construction (AEC) domain coupled with functional databases.

2. Sustainability assessment and tools

Green/Sustainable architecture is no longer a current phenomenon. It is increasingly being addressed in the building industry by different sustainability assessment standards (Solomon 2005). Krygiel and Bradley (2008) state that "many tools used to measure the impact of sustainable design strategies are not directly accessible within a Building Information Model (BIM) itself; therefore, data needs to be exported to another application or imported from a external data source." A "Building Information Model is a digital representation of physical and functional characteristics of a facility; a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle." (Smith and Edgar 2008)

2.1. SUSTAINABILITY ASSESSMENT STANDARDS

There are many different assessment systems used around the world. Fowler's study (2006) shortens the list first, by combining several rating systems used in multiple countries, and second, by subsuming those that are derived from other rating systems. A summary of two such representative assessments standards are given below.

The British Research Establishment (BRE) was the first to develop an environmental impact assessment method, BREEAM, British Research Establishment's Environmental Assessment Method. Subsequently, other countries adopted the BRE approach in developing their own assessment method (Reed 2010). BREEAM has become the de facto measure of building environmental performance in Europe "BREEAM" (2011). There are versions specific to the UK; other versions are tailored to countries or regions to address specific environmental issues and weightings; construction methods and materials and reference to local standards. In assessing a building, points are awarded for each criterion. The points are then summed for a total score. The overall building performance is awarded a "Pass", "Good", "Very Good" or "Excellent" rating based on the score. BREEAM major categories of criteria for Design and Procurement include the following: Management, Health and Wellbeing, Energy, Transport, Water, Materials, Land use, Ecology and Pollution.

In the US, from the onset of the United Green Building Council in 1993, there have been releases of different versions of its rating tool LEED for various building types, the most current being LEED 2009 (this applies to five building types-new construction, core and shell, schools, existing building and commercial interiors). This assessment system has six main categories; Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Air Quality and Regional Priority and Innovations in Design, each addressing specific environmental concerns "USGBC" (2009). Within each category there are specific design goals that have to be met for any particular LEED certification, namely, silver, gold or platinum. Each goal is worth one point; the final certification is based on evaluation of the goals documented.

2.2. ASSESSMENT METHODS

Sustainability assessment criteria are evaluated by quantitative and/or qualitative measures. Quantitative measures reflect numerical values for instance, annual energy use, water consumption, greenhouse gas emissions, volume of reused material and so on.

On the other hand, qualitative measures use comparable measurements such as the impact on ecological value, or rely on user testimony, for example, that certain procedures have been followed. Qualitative criteria of assessments are difficult to encode as they are subject to evaluation from unbiased third parties (Nguyen et al. 2010). It takes time and effort to input data, and varies in interpretation by the different professionals (AlWaer et al. 2009).

An assessment criterion can be evaluated whenever the relevant information is available in the building model. Although this seems straightforward, in

reality this involves transformations, which may entail subjective judgement. A simple example is 'floor area'. In different building information models it can be named as as 'NetFloorArea', 'NetArea' and 'GSA BIM Area'- all referring to the same value of the 'floor area'. There are other similar interpretations for the numerous building elements that are involved in the exchange throughout the AEC domain, Some of these confusions can be avoided if the information is stored in a standard building information model.

2.3. BIM AND INTEROPERABILITY

According to buildingSMART (2010) "BIM standards will integrate standards used in the AEC industry". Current standards include the Industry Foundation Classes (IFC), ISO standards, BIM templates and Construction Operations Building Information Exchange (COBie) (East 2011, buildingSmart 2012). According to the National BIM Standard Project Committee, "A Building Information Model is a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward." (Smith and Edgar 2008)

There are commercial software, which provide BIM solutions, for instance, Autodesk Revit Architecture, Bentley Microstation Triforma, and ArchiCAD by Graphisoft, Inc. These BIM tools employ their own proprietary data structures for representing a building and other design information (containing graphical and non-graphical information). Figure 1 depicts a typical data exchange set up.

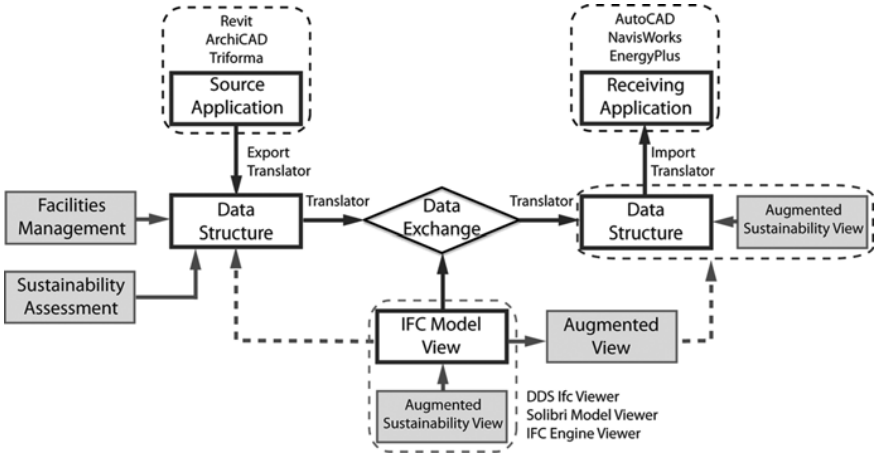

Figure 1. Current Data Exchange from software to another via IFC translation.

The ideal exchange, highlighted in blue in the figure, involves just IFC, which is an extensible 'framework model' to cater to a large set of consistent data representations in the AEC domains (Eastman et al. 2008). It is built using the ISO-STEP EXPRESS language. In practice, IFC can have multiple implementations. Consequently, BIM tools with good IFC import/export translators may still only be able to exchange very little useful data.

For this reason IFC translations from source applications have to be enhanced, perhaps, in stages. Such enhancements need to be considered carefully when used by exchanging applications. For example, there are viewers for IFC model geometry and property, which display attributes of selected objects and provide means to view data in different sets of entities (Eastman et al. 2008). Despite variations in object representation, efforts are being made to define IFC more uniformly and precisely. IFC models are non-proprietary, and as such are increasingly being adopted by governments and agencies (Eastman et al. 2008). However, generally, IFC models do not contain information sufficient for sustainability evaluations. In order to share design information from a software tool, and sustainability related information, we found COBie to serve as a suitable data structure to integrate the necessary building information and evaluation requirements.

2.4. COBIE AS A DATA STRUCTURE

COBie is a format primarily intended for use of managed assets. In this data structure, information is cumulatively provided during the design, construction, commissioning and handover phases of a building. The information includes room lists and area measurements, material and product schedules, construction submittal requirements, construction submittals, equipment lists, warranty guarantors, and replacement part providers, which are normally included in several different places within current contracts (East 2011). The objective of COBie is not to alter the type of information that is required, just to standardize the format of that information to save building owners and occupants, having to rekey the information multiple times. We adopted COBie data structure because the format offers a structure that could be used, extended and augmented to drive sustainability assessments with a functional database prototype.

3. From BIM to assessment

For sustainability assessment, we used a LEED NC 2.1 silver-certified building as the case study. The model was prepared in a commercial BIM tool. This was exported first as an IFC model, and then translated to a COBie model.

During translation from BIM to COBie we had to address a number of issues. First, dealing with loss of information during translation. Second, adding information required for LEED assessments; these are external to the model, such as occupant number, area of buildings surrounding the project for site density, type of ground cover and their corresponding their runoff values etc. Third, converting LEED rules into computable form. Lastly, creating a functional database to aggregate, evaluate, and propagate information into LEED submission ready templates. Figure 2 indicates where data is augmented in COBie database. As shown, LEEDDensity is a new sheet that is added to the database. Sheets such as Attributes, Facility, Type, Space, Zone, Systems, and Job have added columns with new fields and rows of data. The sheets Floor, Contacts, Component and Documents retain their original columns but have rows with additional data.

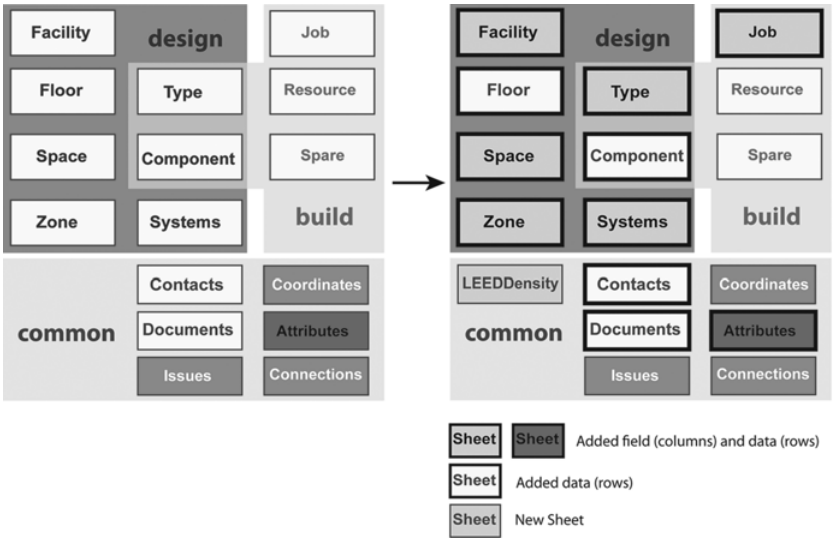

Figure 2. Illustrating the augmentation of COBie for LEED (COBie diagram source: http://www.wbdg.org/resources/cobie.php: Figure 5).

3.1. FUNCTIONAL DATABASE APPROACH

Current research using commercial BIM and LEED requirements have demonstrated the feasibility for semi-automated evaluation (Barnes and Castro-Lacouture 2009, Nguyen et al. 2010, Krishnamurti et al. 2010). In each study, information for sustainability evaluation was added, either by providing exter-

nal databases or by augmenting the model using the capability of the software to store additional information. Figure 3 shows the process of sharing information from a BIM to fill LEED templates for evaluation.

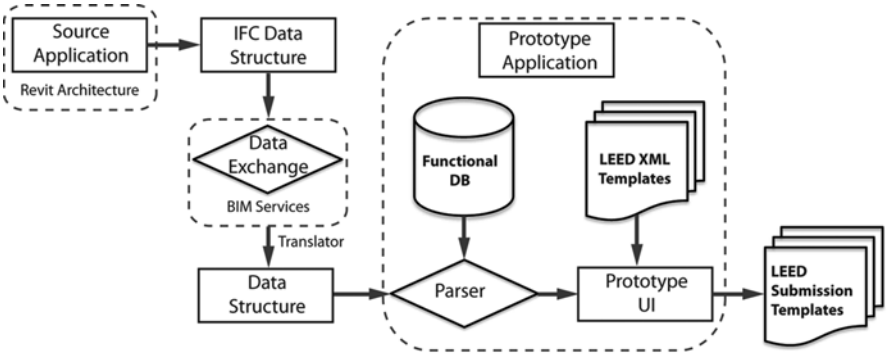

Figure 3. Data sharing for sustainability assessment using prototype.

Since LEED requirements are periodically revised, we can bypass hardwiring the requirements by developing a computable set of LEED rules stored in a database format. Taking the evaluation rules as input, these are then interpreted for real-time evaluation. By providing this additional functionality to an otherwise static database, it allows the application to easily accommodate future rating requirement updates. It enables the multi-disciplinary cooperation from sustainable assessment rule mapping to corresponding building data (and vice versa). The output generates LEED submittals in XML format, which contain aggregated results ready for evaluation. This demonstrates a process where design information can be embedded and retrieved by different software and professionals—from design to sustainable assessment.

3.2. ASSUMPTIONS AND CHALLENGES

We made certain assumptions when preparing COBie sheets for evaluation. These are: (i) building data comes from the translated BIM; (ii) data required for LEED evaluation is augmented, either by adding new data sets to the original COBie format or by augmenting the structure; and (iii) preprocessed data, typically requiring simulation, such as energy usage, or lighting qualities of a space, e.g., whether 75% of spaces are naturally lit, require the COBie structure to be augmented.

The challenges we faced were in identifying the kinds of information that would readily translate to COBie, and determining how and where to store

the requisite information for LEED evaluation. From a data storage perspective the original data structure requires extension, without altering its basic premise and purpose. From a LEED perspective, both qualitative and quantitative measures need to be assessed through the LEED queries. Qualitative measures are verified by the presence or absence of certain documents as required by LEED—these are stored in the spreadsheet named 'Documents'. Quantitative measures are processed by queries to mapped entities in COBie, for example, building area, volume of recycled material used, etc.

Data is extracted and collected from the given database by invoking the assessment rules codified in the mapping database. The mapping database maintains the underlying interoperation mechanisms for various data structures. Figure 4 illustrates the integrative process of our prototype application, which takes a COBie database as input, automates data exchange by executing mapping rules in the functional database, and populates the XML LEED templates.

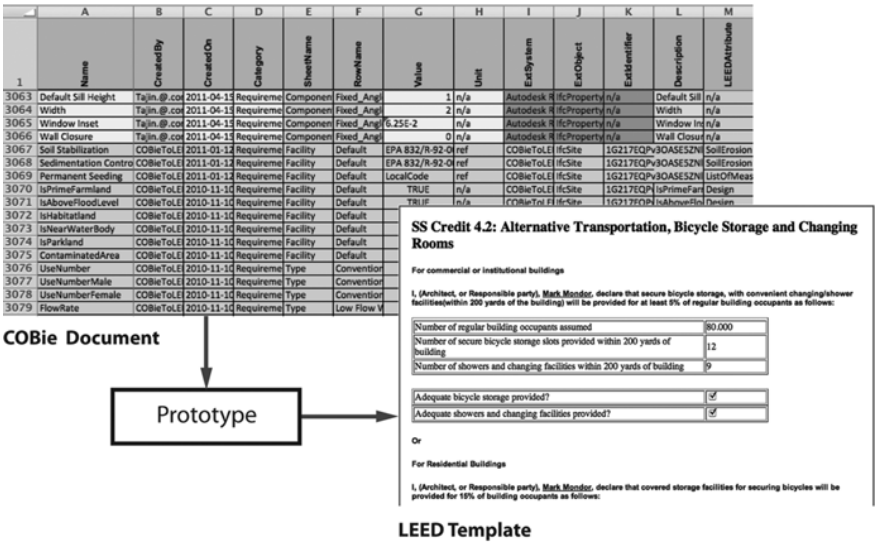

Figure 4. Data Sharing for Sustainability Assessment using Prototype.

4. Conclusion

This study shows an approach to sharing BIM information through a series of inter-operation between various standard data structures, namely, IFC and COBie. We use a database approach to manage the data exchange rules required for sustainability assessments. The prototype application demon-

strates automation of LEED NC 2.1 template generation within an integrative process. The expected contribution is the acceleration of the integration and cooperation between various building professions to pursue improved sustainable environments.

We analysed the nature of the data required to fill LEED NC 2.1 templates. Our analysis show that approximately, on average, 45% of the data is retrieved from the COBie model without augmentation, the remaining 55% is retrieved from data that is added to COBie. Of the added data (55%), 35% of the data can be identified as attributes of the building elements. This includes the data that has to be post processed from simulation results, for example, for energy and lighting. The remaining 20% mainly pertain to queries for support documents that are required for submission.

We are currently exploring this approach to automatically create LEED 2009 templates. This flexible approach will allow for easy update of assessment standard rules as they evolve and change. It also has the potential to be scaled to consider multiple buildings (Krishnamurti et al. 2012). Other assessment standards such as Green Star of Australia or BREEAM could potentially be mapped and assessed. Any limitations observed are due to information loss from the translation from BIM to COBie and its unidirectional flow. The augmented COBie data structure and data cannot be fed back to the initial BIM due to the internal COBie to IFC mapping structure. Identifying, formalizing and mapping of LEED required data to possible IFC entities and/or 'psets' is ongoing work.

Acknowledgements

The work done for this project, Automated LEED datasheets from lightweight IFC models was funded by Construction Engineering Research Laboratory (CERL), which aims at integrating building information with sustainability assessments using COBie as an intermediary platform. However, any opinions, findings, conclusions or recommendations presented in this paper are those of the authors and do not necessarily reflect the views of CERL.

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DISTRIBUTED AND SYNCHRONISED VR MEETING USING CLOUD COMPUTING

Availability and application to a spatial design study

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Abstract. The mobility of people's activities, and cloud computing technologies are becoming advanced in the modern age of information and globalisation. This study describes the availability of discussing spatial design while sharing a 3-dimensional virtual space with stakeholders in a distributed and synchronised environment. First of all, a townscape design support system based on a cloud computing type VR system is constructed. Next, an experiment of a distributed and synchronised discussion of townscape design is executed with subjects who are specialists in the townscape design field. After the experiment, both qualitative mental evaluation and quantitative evaluation were carried out. The conclusions are as follows: 1. Users who use VR frequently and who use videoconferencing consider that the difference with face-to-face discussion is small. 2. A Moiré pattern may occur in a gradation picture. 3. The availability of distributed and synchronised discussions with cloud computing type VR is high.

Keywords. Spatial design; distributed and synchronised environment; communication; cloud computing; Virtual Reality.

1. Introduction

In the spatial design field such as architectural design, urban design, and industrial design, a consensus-building process among a variety of stakeholders such as project executors, designers, neighbourhood residents, users, and general citizens is required. Since it is necessary to share three-dimensional images to study design, 3DCG (3-Dimensional Computer Graphics) and VR

(Virtual Reality) systems have been developed. Design meetings using these systems have been traditionally held in the same-room and at the same time. In recent years, the mobility of people's activities, and cloud computing technologies have become advanced in the modern age of information and globalisation. Therefore, system developments and design trials of a distributed and asynchronous type are used which means that stakeholders participate in the design process at different places and at different times (Maher and Simoff 1999, Fukuda et al. 2005, Matsumoto et al. 2006). This allows expansion of communication opportunities, without a participant needing to worry about restrictions of space and time. However, in communication by text, it can be difficult to take in the nuance and atmosphere of the described contents. On the other hand, since a meeting involving a conversation can solve this problem, communication and decision-making progress quickly. Therefore, this study investigates the capability of a distributed and synchronised type design meeting which allows stakeholders to participate in the design process at different places and at the same time while sharing a three-dimensional virtual space.

2. Cloud computing type VR and experimentation

In a distributed and synchronised type of environment, research on designs supporting a system for sharing three-dimensional virtual space exists. There is a system which allows designers to be physically immersed in their sketches and physical models, literally inside life-size, real-time representations of these, while sharing them remotely with another system of the same sort (Dorta et al. 2011a, 2011b). However, in this research, a framework for two or more stakeholders to participate in a design meeting of a distributed and synchronised type using a standard spec PC is proposed. The data volume of the content of a design study is usually large. Therefore, when drawing 3D graphics with a client PC, a client PC with a high spec GPU (Graphics Processing Unit) is required (Gu et al. 2009, Shen and Kawakami 2010, Nakapan and Gu 2011). A standard spec PC cannot necessarily be used to participate in a design meeting. To solve this problem, the cloud computing type VR (FORUM8, 2011) is proposed.

2.1. CLOUD COMPUTING TYPE VR

The cloud computing type VR system which is a base system of a distributed and synchronised type design meeting is described. In the cloud computing type VR, contents are transmitted by the video compression method of the H.264 standard. Commands about viewpoint change, plan changes, etc. of the

three-dimensional virtual space on the client PC are calculated from the VR contents on a cloud computing type VR server. Then the calculated contents are displayed in real time on the client PC as a video, using the H.264 standard. One user can operate the virtual space of the cloud computing type VR, and the time for which it can be operated is 1 minute. A user who wants to operate is allowed to operate it for 1 minute. Therefore, this system has the following merits: (1) A highly efficient graphics environment is unnecessary in a client PC. (2) Plural participants can share a viewpoint, alternatives, or the VR setup in synchronisation. (3) The VR application version or 3D contents are unified by the management on the server side.

2.2. EXPERIMENTATION

In this research, townscape design is targeted for a typical experiment on spatial design. Firstly, a townscape design support system based on a cloud computing type VR was constructed (Figure 1). The experiment using a distributed and synchronised type meeting of townscape design for 30 minutes was executed with 22 subjects who were specialists in the townscape design field (Figure 2). For this, a designer and a reviewer paired up. The streets in Shimonoseki-city, Japan are extension of 350 meters, and the width of 15 meters. The experiment was conducted from February to March 2011.

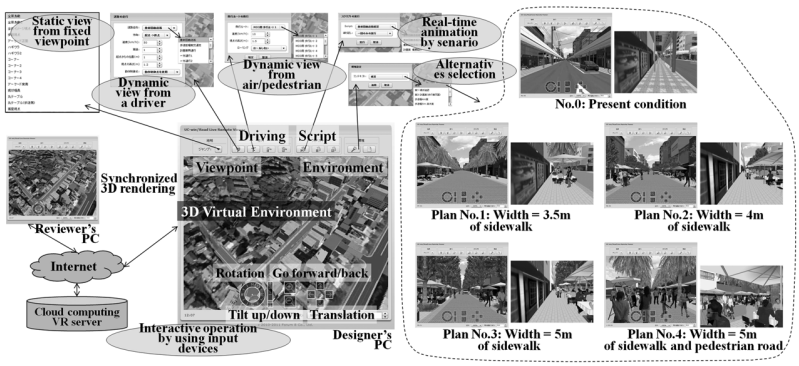

Figure 1. Developed townscape design support system.

Regarding the content of the experiment, the designer presents four kinds of street design proposals, after explaining the current problem. Each design differs in the width of the sidewalk from 3.5 m, 4 m, and 5 m. Also, the way of using the sidewalk and building differ according to the width of the sidewalk. As the method of presentation, after looking down at the whole, a real-time walk-through along the sidewalk is carried out. Since traffic changes with the

change of lane distribution, a simulation of the traffic stream is also carried out. A reviewer asks and comments operating the cloud computing type VR, after listening to a designer's presentation.

Various types of client PC can be used for the experiment. The lowest spec PC with Intel Pentium M of CPU, 480 MB of RAM, on-board type VRAM, running Microsoft Windows 2000 is actually used in the experiment. The display resolution of the cloud computing type VR is 800 × 600 pixels. As regards the 22 subjects, six subjects (27%) used a video conferencing system (Skype), and 16 (73%) did not use one. Seventeen subjects (77%) had used a stand-alone type VR before and five subjects (23%) had not used one.

Figure 2. Experiment screen shot with video conferencing system.

3. Overall evaluation of the experiment by subjects

3.1. EXPERIMENTAL METHODOLOGY

A questionnaire was implemented after the experiment. The questionnaire result was scored using a 5-point scale. Questionnaire items and the result are shown in Section 3.2.

3.2. RESULT

The result is shown in Figure 3. The first item is an influence of latency in internet transmission. As a result, the influence of latency through internet transmission is assessed differently by individuals. A problem which is clear is that it is difficult to quantitatively grasp the change in communication delay time, which is called latency. The meeting was carried on in the experiment, checking mutually the contents displayed on the PC of the designer and the reviewer through conversation.

The second item is a deterioration of the quality of the VR image by internet transmission. As a result, the deterioration was small. A score above four points (80%) was obtained from the subjects who used VR. In Section 4, the

difference in quality between the image of the stand-alone type VR and the cloud computing type VR is verified quantitatively.

The third item is the difference between a traditional same-room and same time type meeting and a distributed and synchronised type meeting. As a result, subjects who use a video conference system and a VR system frequently considered that the difference was small.

The final item is availability for the actual townscape design process. As a result, many thought the system could be used in an actual townscape design process. One comment was that more participation of specialists who work at places distant from the planned construction site had been achieved. When specialists use the cloud computing type VR system at a busy time in a meeting, the system can respond also to detailed changes. On the other hand, differences in the contents of a design may appear due to differences in the colour of the display of the client PC. Preparation by checking a user's PC spec. and internet connectivity is also needed.

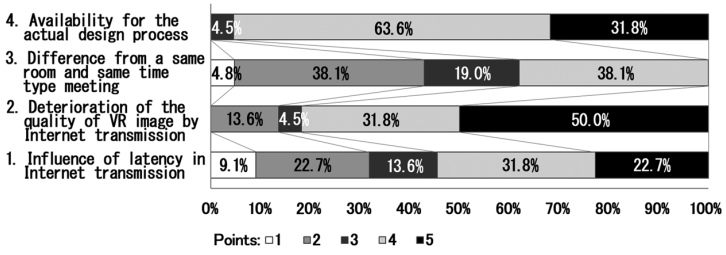

Figure 3. Questionnaire result.

4. Difference in quality of the VR image through Internet transmission

Deterioration of the quality of the VR image through internet transmission was analysed using a spectrum radiation luminance meter, CA-2000A (Konica Minolta Sensing 2011).

4.1. EXPERIMENTAL METHODOLOGY

The stand-alone type VR and the cloud computing type VR displayed on a local host were compared in regard to the quality of the image in experiment No.1. There was no influence by internet transmission in this experiment. Therefore, the differences in the drawing process of the stand-alone type VR and cloud computing type VR could be understood.

The cloud computing type VR displayed on a local host and the cloud computing type VR displayed via the Internet were compared in regard to

the quality of the image in experiment No. 2. In this experiment, the drawing process was the same. Therefore, the difference by internet transmission could be understood.

In order to understand the reproducibility of neutral colours, three kinds of gradation pictures, namely, from black to red, from black to green, and from black to blue, were measured.

As an experimental condition, the indoor illumination at the time of the experiment was 0 lx. The evaluation of the experiment system and an experiment photograph are shown in Figure 4. Moreover, a picture of a townscape design and a gradation picture which is from black to green are shown in Figure 5.

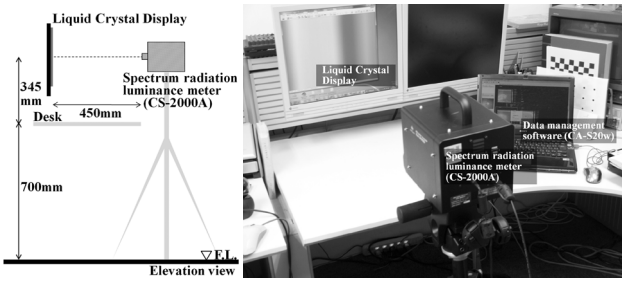

Figure 4. Elevation of experiment system (left) and experiment photograph (right).

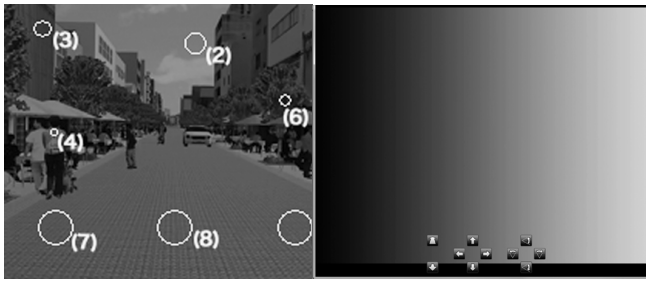

Figure 5. Picture of townscape design (left) and gradation picture (right) for the experiment.

4.2. RESULTS

Results are shown in Figures 6 and 7. The average value of the sum of the absolute value of the difference of the average value of stand-alone type VR and cloud computing type VR displayed on the local host was 0.0024 to nine sample points. Since the ranges of x and y are $0.0 <= x <= 1.0$ and $0.0 <= y <= 1.0$ in a CIE Yxy colour system, the residual error of this value was 0.24%. Moreover, the maximum was 0.0209 and the residual error of this value was

2.09%. Since these values were very small, the difference between the drawing process of the stand-alone type VR and cloud computing type VR displayed on the local host was small.

The average value of the sum of the absolute value of the difference of the average value of the cloud computing type VR displayed on the local host and the cloud computing type VR displayed via the Internet was 0.0023 to nine sample points. The residual error of this value was 0.23%. Moreover, the maximum was 0.0101 and the residual error of this value was 1.01%.Since these values were very small, the difference in the influence according to communication transmission was small.

When a gradation picture was displayed by the cloud computing type VR, Moiré striping appeared. When creating VR content for architectural design and urban design, the possibility that gradation will be used with lighting, sky, etc. is high. When making or applying VR content, it is necessary to pay attention to this.

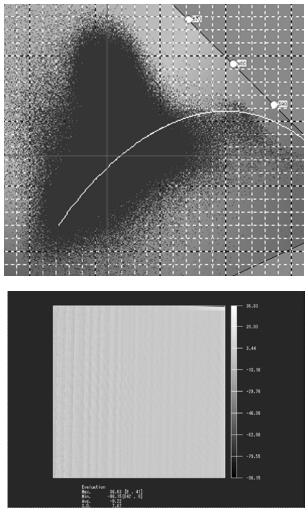

Figure 6. Results (Left: black dots; stand-alone VR, blue dots; cloud computing VR on local host, red dots; cloud computing VR via the Internet. Right: Moiré striping appearance in gradation picture).

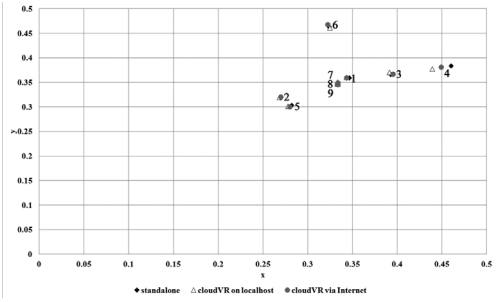

Figure 7. Comparison of xy values of nine samples in the townscape VR of figure 5 left.

5. Conclusion

The contributions of this research are as following:

- A cloud computing type VR system was built and it was approved by a design review meeting following a case study experiment. The feasibility of distributed synchronous type design meetings using the cloud computing type VR is high. It increases the opportunities for specialists in remote places to par-

ticipate in design review sessions. On the other hand, there is concern about whether Internet access would be available at meeting times.

- Those who use video conferencing, and who use VR frequently think that there is little difference between these systems and same-room synchronous type meetings. It is important that participants can check the situation of understanding mutually by video conferencing.
- The influence of image quality degradation with the cloud computing type VR was found to be small following verification using a questionnaire and a spectrum radiation luminance meter. However, a Moiré pattern may occur in a gradation picture.

It is necessary, as future work, through experiments involving meetings of three or more persons, international meetings, etc. to investigate the possibilities for synchronously distributed meetings.

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3A GENERATIVE, PARAMETRIC, AND EVOLUTIONARY DESIGN I

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SEWING TIMBER PANELS

An innovative digitally supported joint system for self-supported timber plate structures

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Abstract. This paper focuses on the joint system of flat panels as parts of a freeform building. This topic is a key area of the ongoing founded research project, in which we investigate nonstandard shapes, realized with standard building materials, namely cross-laminated timber (CLT). We use different discretisation algorithms to overlay arbitrary freeform surfaces with ornaments consisting of polygonal flat panels. We investigate a series of ornaments and their discretisation results on different surfaces. In this paper, we will present and discuss a new timber-to-timber joint system that we developed exclusively for this project. We discuss the results of the load tests that we performed recently and we take a look at the construction dependent requirements of the joint system concerning the tolerances and the geometry and also, how these constraints inform the digital process. As we will discuss throughout the paper, in earlier publications we described the form finding process and the geometrical guidelines for the discretisation of a desired freeform building using ornamental flat patterns. This paper moves one step further as the digital becomes physical and it is closely related to building construction and the computational design outset.

Keywords. Digital fabrication technology; computational algorithmic design; building construction; freeform optimisation; CLT joint system.

1. Introduction

Since the invention of numeric controlled machine tools, it has been evident that digital technology expands new methodologies for designing and control-

ling fabrication processes. Digital technology challenges architects, engineers and allied professionals to extend the limits of feasibility in the design and building industry into higher level of complexities. In our approach, we take advantage of the concepts of "File to factory" and mass customisation technologies, which are based on the idea of mass production that support the digital fabrication of individual components. Thus, the design and fabrication process is fully integrated using parametric strategies (Schimek et al. 2010). Parametric design strategies open up new realms for the integration of building construction issues into the design process at an early design stage and foster an economical scenario for generating nonstandard self-structures.

The use of discretisation strategies in the process for approximating freeform shapes is not new, many attempts have been performed with different kinds of construction strategies and materials, mainly steel and glass but there are just a few examples of freeform structures using solid wood panels like cross-laminated timber (CLT). At the present, there is no existing building with a self-supporting structure employing a timber-to-timber joint system that is also capable of transferring tension loads. The Laboratory for Timber Constructions IBOIS, in Lausanne, has published some interesting results of their research work. Buri and Weinand (2010) has been specializing in folding plate structures using cross-glued timber. In one of the institute's research projects developed by Buri and Weinand, named *Origami – Folded Plate Structures,* he investigated the performance of regular Origami folded plate structures using thin timber panels. A built version of the prototype structure failed due to under-dimensioned joints that could not provide the required rigidity (Buri and Weinand 2010). Research on structures with stronger CLT panels has been considered but, for the time being, there is no published work concerning this issue.

2. Surface and ornament

Published related investigations to the panelisation problem have showcased the possibilities of the top-down approach, where a freeform shape is first generated and then approximated with polygonal flat ornaments, which, according to these publications are produced on a slow track speed. On the other way round, our system allows a live fast track speed opportunity to generate and integrate the aesthetical and physical construction negotiations between the ornament and the overall building shape (Calderon and Hirschberg 2011). In earlier publications (Calderon et al. 2011), we have introduced different Gaussian surfaces and have found out different important relationships between the building shape and the ornamental structure. In particular here, we discuss a large-scale prototype that we are building on the year 2012 (Figure 1).

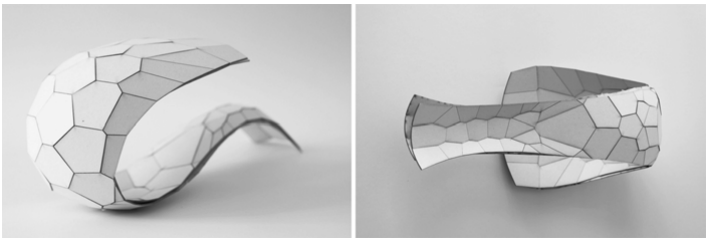

Figure 1. Large full-scale prototype envelope with a pattern mainly consisting of pentagons, hexagons and heptagons.

The surface of this prototype describes positive and negative Gaussian curvatures and it was a great example to explore the possible negotiations of the design ornament and the shape building, its structural capacities and its feasibility for fabrication, assembling and construction.

We designed two different strategies for generating patterns on double curved surfaces. Certainly, in the full-scale prototype we are constraint by the following design criteria: the size of the panels, the number of panels – a maximum of fifty panels are considered-, the topology of the panels – since we intent to use mainly pentagons, heptagons and octagons – and the thickness of the panels. Thus, the examples presented here are intended to envelop a slightly symmetrical parametric shape with a differentiated pattern over the surface.

However, the ornament should also follow, at least, two-fold construction criteria; the grain direction of the timber panels, the geometry of the connector (called Kerto-S, an engineered material, with high mechanical load capacity) and, subsequently, the continuity of the grain direction – distributed by the CLT structures – over the polygonal panels that eventually hold the overall components as a self-supporting structure. Thus ornaments and structure play an important role in relation to the building shape to construct.

As designers, we believe that both the FEM analysis and the loading tests were crucial to understand the possibilities of plate ornaments applied to non-standard buildings, but else, in order to integrate this novel knowledge into the algorithmic design, we identify the necessity to embed the potential that design and engineering aim to combine.

3. Joint system

“Joints are the key to harmonious structures. The challenge for the designer is to produce joints which early communicate their function – the job they are actually doing – and to do this in an efficient and elegant way” (Addis 1994). Joints have significant influence on the structural characteristics; therefore,

the consistency of an architectural structural detail over the structure, as a whole, is crucial for the aesthetical appearance of a building with an exposed structure (Calderon et al. 2011).

In order to negotiate the aesthetics of the ornamental design on a self-supported structure, we know that FEM feedbacks constrain our designs in a two-fold way. The first is that flat panels on a surface should communicate tension forces throughout the whole surface using linear paths without breaking continuity (Figure 2).

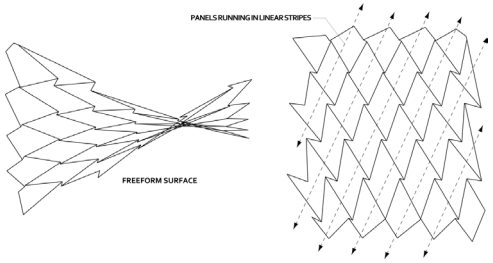

Figure 2. Double curved surface with linear discretisation.
Left: Perspective view. Right: Top view with indication of linear paths.

Caused by the anisotropic material behaviour of timber, a second issue arises, namely deviations between the grain direction of the outer layer of the CLT-panels and the Kerto-cleats have to be avoided as far as possible. Tensile stresses perpendicular to the grain in the panels should be as small as possible (Figure 3).

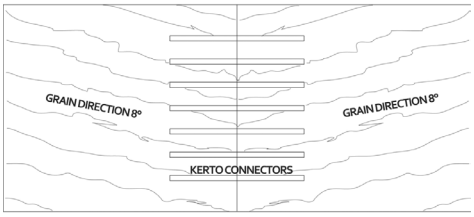

Figure 3. Diagram showing connector orientation and grain direction with a deviation of 8°.

In Section 4, we will discuss different results of the bend tests concerning this issue, besides to this, we also provide general conclusions about the load-bearing behaviour of the joints.

3.1. INVENTION OF A NEW TIMBER TO TIMBER JOINT SYSTEM

In this research project this is the first time that a self-supported CLT-structure is built with a glued timber-to-timber guaranteeing tensile strength joint

system. The building material we are using is CLT, which has an excellent reputation as a sustainable and regenerative material and CLT boards can be easily machined with a large variety of robotic tools including CNC milling machines. Since these structures are intended to be self-supporting i.e. carrying all loads without any additional structural supports, the joints between CLT boards become structural, which eventually transfer positive and negative axial forces, lateral forces and bending moments. The panels are connected with parallel laminated veneer cleats made of Kerto.

At the present, there are no built examples that use such joints for CLT structures (Schickhofer et al. 2010). Consequently, this paper proposes a new joint: the "sewed" joint, whose stitch pattern is similar in appearance to the stitches of a seam (Schimek et al. 2010). Since these joints will be exposed on the exterior of the building envelope, they will have a dominant influence on the appearance of the structure. Thus, being able to control the relationships and the distribution of the connectors is not only a question of load transferring between the panels but also a creative and intuitive process carried out by the architect.

3.2. ABOUT GLUEING, JOINT GEOMETRY AND TOLERANCES

Up to now, we have tested six different connector configurations with seven mock-ups for each configuration. The geometry for the glue joint had to be very accurate in order to meet the requirements of a one component-polyurethane glue, which belongs to the group of reactive adhesives. The glue is approved by the German Institute for Building Technique (DIBt), requires a wood moisture between 8 and 12% and a bonding pressure of 0,6 – 1.0 N/mm^2 with a maximum width gap of 0.3 mm between the Kerto-cleat and the slot (DIBt, 2011). Consequently, we had to angle the slots conically. In doing so, we are securing a very tight fit of the connector when it is inserted (Figure 4).

Figure 4. Gluing process: KERTO-S cleats are being inserted into conical slots.

Aside to this, we tested a two component cast resin, which is much more tolerant in terms of the width of the gap that can be up to 4 mm. The latter is a very important feature concerning the CNC-milling tolerance. But due to the relatively low viscosity of the product we had two major problems handling the material: since it was running away, what wasted almost 50% of the very expensive glue and, eventually, this also soiled the panels.

The gluing process for the test configurations was very revealing since we empirically could collect information about the effectiveness of the assembling process. Considering the workflow at the building site we decided to use the one component glue accepting tighter tolerances of the geometry.

3.3. MILLING

The first series of panels for the load tests were milled on a 6-axis industrial robot machine, which results did not fully satisfy, due to vibrations of the milling head – when it had to cantilever widely in order to reach the backside of the work piece – that eventually resulted in uneven flanks of the slots (Figure 5).

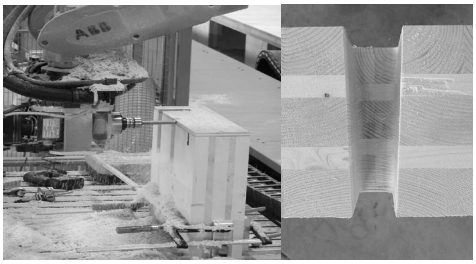

Figure 5. Left: Milling with 6-axis robot arm. Right: conical slot.

Consequently, we switched to a five-axis router, which led to feasible results, demonstrating that the slots could be produced within the required range. Working with such precision is not common in the carpentry business on site and can only be achieved under factory conditions. Once we could fulfil the accuracy – pre-defined by the specifications of the glue manufacturer – we started to glue our test series.

4. Load tests

4.1. CONFIGURATIONS

A first series of load tests of 30 samples with four different configurations were performed on early 2011 in order to test the shear resistance of the con-

nection. In particular, we were looking at the parameters of the connector geometry, the used adhesive and its application, the position of the connector and the slide-in direction. The characteristic value concerning the shear forces of the Kerto-cleat was reached. We could observe both a collapse of timber and a collapse of the glue.

The purpose of the second test series was to verify the bending strength of the connection with configurations that might be used for the prototype structure, in other words, the load bearing behaviour of mitred butt joints, the load bearing behaviour of a non-grain-parallel glued Kerto connector and the impact of the insertion direction. In this second test series, we tested six different configurations with seven samples each.

4.2. LOAD TESTS FINDINGS – OPTIMISATION

As a conclusion of the load tests, the average utilisation can be specified with some 65–70% of the panels own specific load utilisation, which is very promising for our project's prototype. The estimated size of the connectors (Kerto-S) was proved to be right dimensioned. This was verified by tension and bending load tests on single connector ribs. In both cases, the expected forces were reached. No significant differences have been evidenced inserting the connector's top-down versus bottom-up.

Five criteria define and constrain the aesthetical appearance of our innovative joints: size, geometry, position, orientation and quantity of connectors (Calderon et al. 2011). Following the results of the load tests on mock-ups two of the criteria, size and geometry, have been empirically assigned. First, the engineers delivered the FEM stress analysis of the shape designed by the architect. The model used in their analysis is an ideal model i.e. the orthotropic characteristics of the timber material is not taken into account but the mechanical parameters of the material are estimated. The orientation of stress components suggests the required grain direction of the relevant member. The range of section moments defines the number of connectors to be inserted. This early stage FEM stress analysis represents a "calculated estimation" that conducts the design interventions concerning the connector position, distribution and orientation.

The geometry and grain direction is already pre-defined in the digital 3D-model, which establishes the connector direction. Then, the number of the connectors is calculated, based on the value of the applied loads on the edge to be examined. Then, the new geometry of the connected neighbouring panels is generated. Technically speaking, to calculate the discretisation of the surface, the thickening of the panels and the connector geometry of all neighbouring panels, we use an add-on for Rhinoceros that is programmed

in C++ performed in Grasshopper using a C# component. In other words, we designed a parametrically controlled system capable of discretising a freeform surface, generating the panel geometry, the grain-connector direction, the connector's geometry and calculating the number of connectors based on the loading values. Consequently, we use this method – which work on a live and fast track speed – to investigate different ornaments on the same shape and negotiate both structural and aesthetical features of the joint patterns, which are dependent on the FEM pre-calculation in order to define an overall design from the outset (Figure 6).

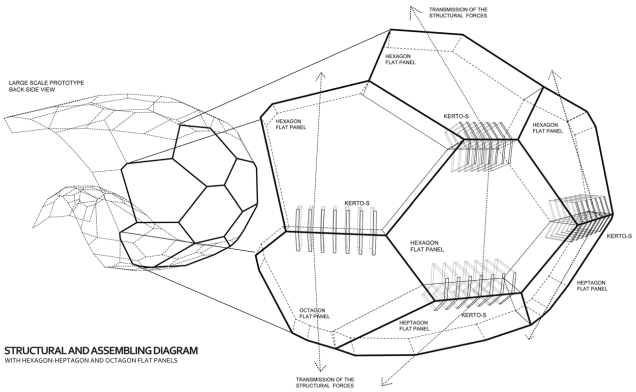

Figure 6. Load-time diagram of test configuration V300ANU-9.

In Section 3, we discussed the relationship of the grain direction of the panel's outer layers and the orientation of the connectors (Kerto-S), which should be close to the grain direction angle. Besides the other configurations, we tested one with a grain deviation in relation to the connector orientation. We did this because in earlier considerations – based on studies of the load behaviour of CLT – we assumed that the alignment of the connectors with the panel's grain direction would have to follow the same angle (Schimek et al. 2010). The test results of this configuration demonstrated a decline of the load capacity that was not too significant in relation to the average capacity and the curvature of the prototype (Figure 6).

5. Assembly

As we can repeatedly observe in digital workflows, the integration of the digital model throughout the design process is not a problem but when the structure becomes physical the problems manifold. "One would not believe how much manual work is required for digital production", Scheurer (2009) states in an interview. By saying so, we are considering major issues, with the physical

assembling of the full-scale prototype, at the required falsework level, which has to be as accurate as the structure itself. The job of the falsework is to secure each panel's position during the assembly process and must not allow inaccuracies in any direction. We know the latter is difficult to achieve, therefore, we consider a strategy of a flexible falsework construction that moves with the building process. Consequently, we have to permanently re-check the position of each panel during the assembly process, preferably with a 3D coordinate measuring laser system in order to be able to compare the coordinates with the digital model.

6. Outlook

We are currently working on a strategy for assembling a large prototype, consisting of approximately 50 panels that are being assembled to a structure of 10 × 4 × 4 m. We anticipate that the falsework supporting the structure during the construction will become a critical part of the assembling process. Consequently, the falsework has to be designed in the same digital model and digitally pre-fabricated with the same precision as the prototype structure. Following the cyclical design and fabrication process of the project, the digital process for optimizing the joint system will certainly benefit from the information we collect during the physical assembly of the prototype and thus, integrate both digital and physical negotiations and constraints in one single embedded system.

Acknowledgments

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INTERACTIVITY IN VIRTUAL REALITY

Learning from 3d game design tools

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Abstract. The present paper tries to explore the potential of visual-heavy tools in the creation of virtual reality worlds, with an emphasis on tools borrowed from 3d electronic games. Compared to earlier approaches in virtual reality creation the paper focuses on game design tools and provides a basic framework for interaction in virtual reality, based on classic rather than digital representations, which is then expanded using digital representations. In the second part of the paper a game creation tool is assessed based on its potential not only of usability but also on guiding the designer in specific paths to designing virtual worlds. The assessment is based on a case study of interaction design.

Keywords. Virtual reality; 3d game design; open source.

1. Introduction

Why use virtual reality when reality is so complete? Why bother with the fuss of constructing a semi-automated, failed, copy of reality? The promise of virtual reality remains strong as ever: one can create whole worlds out of nothing, populate them, give them a beat and a rhythm, but most of all give them possibilities (Alvarado and Maver 1999). The promise of virtual reality remains, still after all those years of under-delivering, of the super human: it provides a path to experience those that are out of reach in real life.

In the same manner, even in situations where there is no real counterpart, Virtual Worlds are mappings, a metaphor of the real world. This is evident in the fact that the most successful ones have a complete, well structured mode of interaction since this is the one trait that makes the world come alive, even if graphics fail to stand up to modern standards. Interaction is again a mapping;

the mapping of a real or expected behaviour to a counterpart in the Virtual World. Of course, there are exceptions to this, where exceptional virtual worlds have interaction unexpected from the user but that grow familiar only through use. Use of course comes from repetition and repetition emerges from having fun when you use or do something.

This is where game design becomes important. Beyond the 3d virtual worlds where the user participates in a simulation, games are virtual worlds where you are supposed to enjoy yourself, in a variety of ways. In designing them the designer does not just construct a world where something happens, but where something enjoyable happens for the user (with a variety of connotations as to what enjoyment is). In this the nature of the design tools to create a 3d game has to be considered. Assessing the technical side of one's tools is one important element, but also assessing and designing the interactive, fun, enjoyable element of the virtual world is another, maybe counter-balancing to the technical element. But how does one design and assess the fun element in a game, and by extension a virtual world?

2. Framework for interactivity in virtual reality

One of the problems that the current researcher has today in assessing virtual worlds is that a consistent theoretical framework is missing from most of the research literature in terms of interactivity in virtual reality. Earlier efforts have mapped the elements of design of Chinese gardens to a methodology for designing virtual reality, resulting in a set of spatial organising principles that can be used in designing virtual environment (Lin and Chien 2003). Other researchers (Champion et al. 2003) have used interactivity as a means to end, namely to 'engage' the user of virtual reality in foreign cultural heritage sites presented in virtual reality.

In other cases (Nitsche and Roudavski 2003) "narrative" plays an important role in driving the virtual world, or virtual reality is seen as a tool to enhance communication or as a tool to construct a "design of place" (Paterson 2006). Other parts of the literature suggest that building "mood" in a design construct is important (Rafi et al. 2000). All these cases suggest that interaction and interactivity is a vital part of virtual worlds, even in its simplest of forms, for example in simple navigation in a virtual world. In all cases mentioned above interactivity plays a vital role in reinforcing the feature of the virtual world examined by the respective researchers. In short interactivity supports both the technical side of virtual world design and building and also the emotional, evocative side (Figure 1).

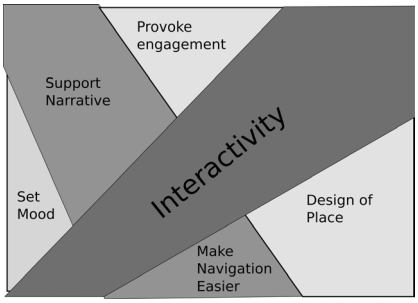

Figure 1. Interactivity support of both technical and evocative traits (interactivity transcends the bands of mood, narrative, navigation, engagement).

3. Interactivity, a supportive element of virtual worlds

Technically, interaction is the passing of messages between two entities (McCollough 2005) in our case the user and the computer. Interactivity supports spatial organisation in a virtual world by enhancing visual or aural feedback in user navigation. Feedback in the sense of passing messages does not mean that the user just interacts with the part of the computer that transmitted the message, but also that the message gets processed and the user acts in the environment with other parts of the computing platform. That does not of course mean that poor spatial organisation can necessarily be enhanced or corrected by improving interactivity. One example where interactivity elements from games enhance the spatial experience for the user are the common heads-up displays employed in first person or third person perspective action or adventure games: an interactive map displaying the users location, navigation landmarks or signs or other important spatial data is superimposed on the display of the "hero"-user inside the game. In recent games of the last five years these features have become even more "advanced" displaying GPS data and position tracking for the avatar of the player (GTAIV).

In terms of user engagement and the creation of mood interactivity is important in the way that most of the time it enhances user engagement specially in those cases where the user does not even notice the interactive features. For example vivid, almost real simulation of physical properties of objects allows the user to experience a richer environment and allows exploration of the features of the virtual world. Games, to achieve even greater user engagement, incorporate real physical feedback for the user's character like inertia, gravity, friction or even near-real-world features such as objects that when hit break in a random manner every time instead of playing a previously configured animation (HL2, HAV). Another example where game interactivity supports user engagement is again via heads-up display of information on screen, in

situations where user's input requires help. These cases are present in various computer games or tasks inside games, from puzzle solving to speed tasks to selecting an object from an inventory (Champion et al. 2003).

In other aspects of virtual worlds interactivity drives forward narrative and supports the construction of space and place. This is the weakest form of support that interactivity provides compared to the ones described above, but nonetheless it can create important aspects and enhancements in those features. Narrative is handled through consistency in the interactions the user has to take inside a game or virtual world and in building a specific consistent interface and user set of actions. Accordingly design of place is built interactively using subtle clues, either visual or aural in virtual reality. Here the design of the clues proves important as the designer selects the proper clues appropriate to the mood, setting, and character of the place portrayed.

4. Interactivity design process

The interactivity issues described above can be understood as a set of issues a designer of virtual world can take into account in building the interactive features of the world. This description of course does not provide a concise design strategy on how to design a virtual world, where there a lot of factors taken into account exactly like any design exercise. One of these factors is the software used to build the virtual world. Even if not all other factors are considered equal software plays a crucial role in creating interactivity mainly because the process of designing the virtual world in software is very close to the finished product. In terms of the design process there are software concepts and software tools that drive into different qualities and level of control of interactivity. All of them however incorporate a cycle of design > test > validate > design. Software tools that ease the process of design and testing and at the same time make the effort of going from design to testing easier are better for virtual world design. This happens since they allow the designer to go from design to testing and back, allowing for quick changes and manipulations.

5. Case study and software

We assess an open source design tool for Virtual Worlds in its capacity to create a game where there is a serious purpose while at the same time building interactivity with the player in an enjoyable way, based on the assumption that an effortless design of interactivity leads to better virtual worlds. Minimising of effort in interaction design is important because when designing a whole world the user tries to impose order on chaos. The software assessed is Blender, a kind of Swiss army knife of graphics in a complete suite: it can

handle modelling, rendering and animation relatively well and has an integrated game engine. The case study is a project called "Space, City, Play" developed by the architecture office archIV+ (Figure 2).

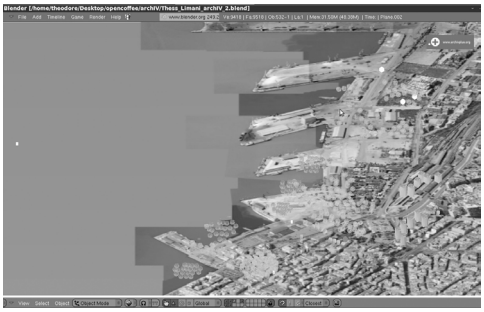

Figure 2. Screenshot of Space, City, Play.

The project focuses in the emergence of bottom up strategies to explain, reformulate, design and plan the urban environment. The case study analysed here is a project by the architecture office ArchIV+ (Figure 2). The project focuses in the emergence of bottom up strategies to explain, reformulate, design and plan the urban environment. It is an installation that showcases how urban design and planning works to a non-trained audience by allowing the audience to interact with an axonometric plan of a city, transforming and redesigning the city. The specific city presented here is the city of Thessaloniki, Greece, a coastal city of 1 million inhabitants, containing traditional architecture, Roman and Byzantine remnants and monuments but also modern, contemporary architecture. Two phases were distinct in the project: the initial development and concept design, that largely happened using pencil and paper along with conventional cad tools and the software development phase where the concept "materialised" in software. Using simple "rules" the aim is to strengthen the blue-green structure of the city, re-examine the relationships among urban space green space and producing multiple and alternative transformations of the city. The public installation of the project uses interactivity and augmented reality to let participants influence a generative system affecting the city.

The designers created a large map of the city of Thessaloniki, using data from Google Maps, Google Earth, and OpenStreetMaps (OSM). Four elements are identified throughout the city: water, green, built elements, circulation. These four elements were objectified in the creation of the project. The designers initially conceptualised the relationships between these elements using simple rules that should govern their interface: For example green areas can co-exist with water, built elements attract other built elements to create

density etc. In essence the city is analysed in various entities that interact to form the city: urban blocks, green space, water resources, circulation and communication systems etc. The goal here is to create different strategies for transforming the city, by combining many of the initial rules of the designers rather than having a clear target from the beginning. After the initial concept was created the designers used Blender, specifically the Blender game engine, to create a working prototype for the project (Figure 3).

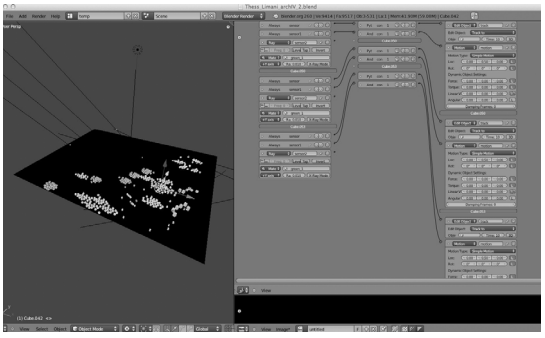

Figure 3. Screenshot of Blender game engine during development.

The four elements along with the rules that govern their behaviour were design inside Blender's game engine. The augmented reality part of the project was an interface of the processing language and Blender, where a camera would see the colour markers used by the audience. Each colour marker would represent a different element, and each marker could be moved by the audience trying to create for example more green space unto the main screen projection. The camera then would pass that information to a processing language script that would parse the data and detect movement of a specific marker. This detection of movement would then get translated to Blender into a movement and subsequent creation of that represented element in the specific part of the screen. Effectively the system was designed so that the users would be able to "paint" green, water etc. using the colour markers on the screen. However the initial rules modelled inside Blender would calculate a new condition every time movement was detected and the game engine would try to enforce the rules along with input from the users. The complexity of the relationships between the initial rules of the designers and the audience's input made it difficult to predict the exact behaviour of the system once given to the users/audience.

The installation can scale from a simple map of the city to multiple cameras transmitting images of the city in real time in the installation space. The participant citizens can then decide and try to affect their city, in a mix of pro-

jections of new construction, new green or water space etc. The final result is rendered in real time and can show the result of conflicts among different policies (interactions among multiple users) and not the result of one user. In the case study there is no end or definite goal, our implicit goal was to design and play with a virtual version of the city of Thessaloniki while allowing the final users "design" their own version of the city.

5.1. OPEN SOURCE SOFTWARE: TOOL TESTING

Blender aims to solve the "effortless interaction" problem by integrating the game engine and making easier to produce a virtual world. The designer just defines some properties on objects and the objects can then start interacting between them as soon as the designer presses the key "P". In a sense game design in Blender does happen bottom up rather than top down. This at first appears to maximise rather than minimise effort in the design of the game, since the designer does not have at first a clear pathway to perfect interaction design. The near instant "playability" of the Blender game engine allows one though to test the interaction immediately, without any data translation or complicated compilation. The top down decisions the designer of a virtual world will make will be expressed in the relationship she establishes between objects and their environment. In Blender the process of linking between objects and their data drives interactivity, and to master the top down approach one has to master the specific process of linking between objects, their data and their behaviour. Blender nonetheless does not allow changing the content, behaviour and interactivity of the game while it is running.

The team decided to standardise on Blender for this project, as it allowed an easy manner to exchange information through its all containing file format, and besides the steep learning curve everyone was able to edit files and provide their own interactivity features for testing, since the tool allowed for a graphical manner of programming the features and behaviour of objects, at the same time with constructing the 3d features of the object. During the formation and design of the project by ArchIV+ the use Blender by the designers were observed, in terms of interactivity features that the tools allowed to be incorporated in the design seamlessly. The focus was the effortless incorporation of interactivity and not the post-rationalisation of the design so that it could accommodate interactivity. This involved a revisiting of the initial concept idea for the project Space, City, Play, as the initially chosen design rules were abandoned for rules that could support interaction further, and allow for citizen participation (interaction) rather than the follow the designers' intention. On top of that, the fact that different tools were used for different parts of the project, created a mental distance between graphical objects and interactive

features. This can be attributed to the manner the Blender game engine models objects. The geometry of the object is the basic property and then the designer can model behaviour in two ways: either assign basic behavioural if-then rules to objects or create much more complicated properties where the property of the object will affect the behaviour of another object. This complexity was not envisioned in the initial concept of the team leading to changes in the implementation of the rules during project development. In effect the designers realised that the complexity of the tool was affecting the manner in which they would implement the project even if the initial concept appeared straightforward in terms of implementation. From the opposite direction some of the rules implemented n the design strategy were adopted by the manner the game engine works in Blender: instead of mapping the behaviour directly, the rules were mapped as properties of objects and then these objects would trigger behaviours from the environment or other objects as well.

6. Ways forward

Programming interactivity into a virtual world does not just involve the addition of a layer of behaviours on objects. It involves a careful design of the behaviours in close coordination with the rest of the characteristics of the virtual world. In this sense, virtual reality worlds tend to function as Asian garden do: Japanese and Chinese gardens are designed as cultural forms, made to represent or symbolise from Nature as much as possible. There are three methods used in designing Japanese and Chinese gardens: Reduced Scale, Symbolisation and Borrowed views (Toshiro 1998). Each one has a specific relation to reality, the first is the "suggestion of a wider landscape through the use of partial elements in a scene" (Chen 2009) reduced scale representation of the real world, the second uses real objects as a kind of symbol for a real counterpart heavily employing generalisation and abstraction, e.g. white sand for representing the ocean, and borrowed views where a mix and match is used to identify a fictional real landscape, especially when the garden designer accounts for movement of the viewer or standing stationary in the design (Chen 2009).

In this sense, the Asian gardens design; where maps of real world settings are created in a different setting serves as a guide on how to integrate behaviour in the design of the virtual. The academic community still misses the common ground to discuss interactivity as a vital part of virtuality or even augmented reality. However the author expects that assessing design tactics and at the same time tools that offer the possibility to explore and implement these tactics will allow future virtual designers to engage with interactivity in an integrated manner rather than a feature added manner.

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PARA-TYPING THE MAKING OF DIFFERENCE

Associative parametric design methodologies for teaching the prototyping of material affect

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Abstract. PARA-Typing the Making of Difference presents design research and instruction into the use of constraint based digital and analogue modelling techniques and the development of associative parametric models to simulate highly differentiated fabricated form. These design research projects were conceived as manual analogue generative processes for prototyping modularity and serial differentiation. Then through associative parametric design technologies and methodologies, modular fields were design explored and developed in concert with material properties and constraints. Utilising digital fabrication full-scale installations were designed, manufactured, and constructed as tiled walls that created differentiated space within site-specific configurations.

Keywords. Generative design; parametric modelling; prototyping; digital fabrication; tectonics.

1. Introduction

PARA-Typing presents design research which describes the development of projects that moved from analogue and material based form finding to digital simulation, aggregation and fabrication and back to analogue prototyping at scale. It begins with an initial exploration of patterns and the invention of basic units or modules aggregated into a field that are systematically repeated. The initial analogue design pedagogy lead the studio to begin to develop modular conditions through examining various origami-like tessellation methods in

the medium of paper prototyping. This process proceeded to a parametric analysis of the basic module and its overall effect on the greater field and the exploring of capabilities of manipulation and mutation. As a bottom up approach, rules were then applied to the module and its relation to its adjacent neighbors as well as its relation to an overall field being created. As a conclusion to these initial steps of investigation, four modular fields were selected to undergo another series of examinations and developments both through analogue means with the continuation of paper prototyping as well as with the use of digital tools to begin to generate differentiation in the field through the use of parametric computation. With the use of digital fabrication methods four full-scale installations were constructed out of 2-ply chipboard to create spatial apparatuses that defined site-specific spaces. These explorations were an in depth analysis of paper and its tendencies under various stresses, and of the pushing the paper to its structural limits once the installations were assembled in their final configuration. The research presents the experiences and lessons learned for teaching design exploration processes and paralleling digital and analogue techniques in pursuit of making highly differentiated form. The research discusses the methods of translation of design intent and material affect into digital methods and then back through digital fabrication for analogue material assembly. The research presents the successes and limitations of the resulting interface between analogue fabrication and construction process with those of digital abstraction and solution space forming. The projects enumerate unique design research and design teaching methods allowing the constraints of material to inform digital process and prototyping of material connection, tolerance, structural performance, and the parametric-prototyping or *PARA-Typing* of material affect. The design research discusses prototyping and the effect of parametric modelling as a prototyping methodology with its ability to promote the materialising of difference and tectonically realised architectural systems.

2. Project precedents and motivations

Our design research builds upon three areas of precedent, parametric design, prototyping and pedagogy, and material and computing. Parametric design enables quick modifications to design solutions through associative geometry (Aish and Woodbury 2005). It is also a successful method to teach design strategies about structural design problems (Woodbury et al. 2007, Holzer et al. 2007, Flager et al. 2009). A complex model designed in a parametric software can be realised by computer aided fabrication and precise assembly of structural components (Sass 2009, Fleischmann et al. 2011). Problem descriptions developed with parametric design requires construction of rapid prototypes in

the early design stage (Hudson 2009). Digital fabrication technologies entail going from CAD/CAM models to precise 3D manufacturing of components or prototypes by computer-controlled machinery. Rapid prototyping allows fabrication of complex physical models in the product development stage for hands-on learning of building structure (Griffith and Sass 2006, Oxman 2009). Rapid prototyped models can be used to study material characteristics, assembly process, and fabrication flow purposes (Kilian 2003).

A designer has to evaluate the material system in computational models by considering its material characteristics, geometric behaviour, manufacturing constraints and assembly logics in order to understand the complex relations between form, material and structure (Hensel and Menges 2006, Menges 2007). Material exploration, modelling and analysing non-uniform elements structurally are essential to deriving an architectural idea (Iwamoto and Scott 2011). Understanding the material properties in such a design project is useful in a learning environment as it helps students to understand the sensibility between analogue material systems and digital precision (Cabrinha 2010). Digital Fabrication in a classroom environment also has pedagogical benefits through materialisation of concept and interaction with physical artefacts (Sass and Oxman 2006). The design process of translating CAD/CAM models into full scale construction familiarises students with rapid-prototyping equipment and precision cutting tools by introducing them to machine shop environments (Iwamoto 2004). This research builds upon the precedents enumerated as well as aims to identify the gaps of going from digital design to analogue fabrication in a studio environment.

3. Project methodology

Given the design intent of the course project, the materialising of difference and the constraints of the paper multiple methodologies and approaches were undertaken by each of the four student groups. The initial investigations done by each of the four groups were strictly an analogue process of repeated experiments of constructing varying modules through paper prototyping. With the basic modules studied and developed, the choice to transition into a digital interface was undertaken to begin to create parametrically driven surfaces that would generate deformation within the module and within the field. At this stage in the project various computational tools were used including Rhinoceros, Grasshopper, RhinoScript, and Digital Project to construct parametric systems, which instigated variance within the modules and fields. The digital phase of the project included often multiple platforms and varying computational techniques to achieve their own parametrically driven differentiated surfaces.

Based on analysis of a specific site condition, each group developed a parametric surface for design exploring the patterning and control in form finding difference. Then the process of digital fabrication was undertaken to disassemble the various components of each system to be sequentially labelled with its reference to its context within the field as well as its connection to its adjacent neighbouring modules. Then the process of unfolding allowed the individual groups to systematically order the parts in a manner that would allow an efficient reconstruction of the disassembled members. With the use of other programs such as AutoCAD and RhinoNest, a plugin component of Rhinoceros, laser cut files were created for the final part of the digital fabrication process. The benefits of utilising RhinoNest allowed for the program to create the optimum layout for the numerous pieces to reduce the amount of wasted material as well as the time it would require to nest manually. Once the digital elements of the project were complete the last stage was to revert back to an analogue procedure and organise the numerous components of each project and assemble the full-scale apparatus to its site-specific configuration.

4. Project descriptions and results

The following section describes in detail four group design research methodologies and results. Groups 1, 3, and 4 had three students while group 2 had four. Each followed the general project methodology described above and each design explored and developed unique analogue to digital back to analogue methods. The project descriptions recount modular development, field development, fabrication, and construction sequences.

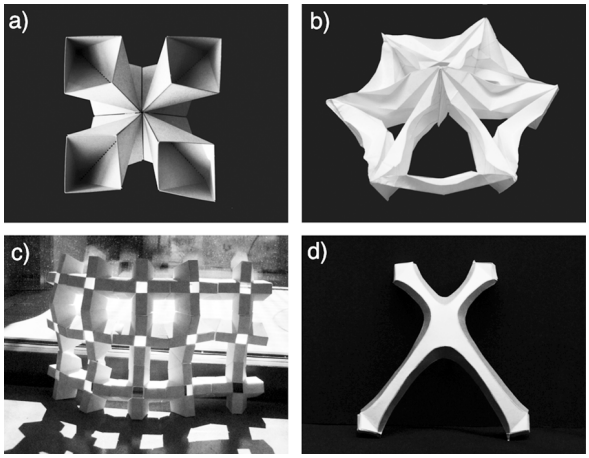

Figure 1. Analogue Module Development; a) Group 1; b) Group 2; c) Group 3; d) Group 4.

4.1. MODULE DEVELOPMENT AND AGGREGATION (ANALOGUE)

All groups began module development by experimenting on a piece of paper. Initial tests involved folding, cutting and creasing to create a module for structural investigation such as rigidity and conformity to curvature (Figure 1). Here, a 2D piece is transformed into a 3D rigid material by using the elasticity of the paper. Groups experimented on modules taking into consideration the field creation. Paper prototyping not only teaches students about module differentiation and transformation but also forces them to figure out how to combine the modules through either face-to-face connections or joints that would allow modules to aggregate and form complex structures. The analogue aggregated modules and field development are shown in Figure 2.

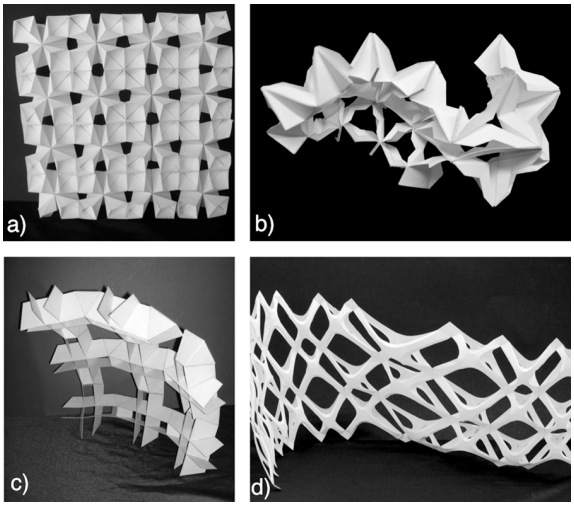

Figure 2. Analogue Module Aggregation, Field Development; a) Group 1; b) Group 2: c) Group 3; d) Group 4.

4.2. FIELD DEVELOPMENT (DIGITAL)

Digital field development was started by using a parametric design tool (Gehry Technology's Digital Project) as shown in Figure 3. The modules are instantiated across a context surface simulating the site where their mutations become apparent in their need to stretch and conform to their adjacent neighbours. Using a parametric tool allowed the groups to determine the manufacturability and adaptability of their designs by creating different context shapes. Students also improved their ability to use a parametric tool, and their understanding of how to create conditions where pieces are not skewed beyond the point in which they were designed to function and be buildable.

All groups visualised their designs in 3D for observation of possible problems. Groups 1 and 2 fixed their context files in problem areas to resolve unwanted deformations. Group 3 and 4 had to re-create other context files in order to finalise their field design. Group 4 switched to Rhinoceros due to not being able to embed the intelligence of the elasticity of the paper within the Digital Project with the knowledge they had. Group 4 also had to create a secondary structure to support their field due to non-rigid connections between the modules.

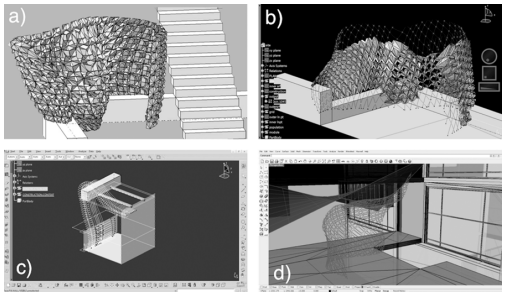

Figure 3. Digital Module Aggregation and Design Exploration: a) Group 1; b) Group 2: c) Group 3; d) Group 4.

4.3. FABRICATION (DIGITAL)

Each group used AutoCAD and Rhinonest to organise and layout 2D flattened individual components translated from 3D configurations to be manufactured by laser cutting tools. Rhinonest allowed for efficient layout on the sheet material, 2-ply chipboard. The laser cut pieces were grouped and labelled for further identification during construction process. The distinct size and custom nature of each module forced groups to layout different 2D sizes for each component, and use a large amount of construction material.

4.4. PRE-FABRICATION, CONSTRUCTION AND ERECTION (ANALOGUE)

Each group followed a similar process for the pre-fabrication and off-site assembly and then on-site erection. Once the full complement of flat sheet pieces were cut the assembly of each module could begin. Groups divided the full construction of the installation into manageable sections and assembled in the studio, i.e. pre-fabricated (Figure 4).

The first group took the corresponding pieces and folding and gluing along designated joints. Beginning with the base of the installation and building vertically the structural integrity of the 2-ply chipboard began to become

compromised from the dead weight of the installation (Figure 5a). Group 2 immediately realised in the construction phase the need for a secondary structural system to help support the field in its proposed configuration. These unforeseen problems and failures in the installation did not allow the group to fully assemble their project in its entirety on site yet the experimental process at which they were able to achieve throughout the process created an extremely differentiated surface (Figure 5b). As for Group 3, construction proved to be challenging due to stress on material and joints created by wind and gravity, another un-foreseen in the digital process. Although it could only be assembled on the ground the designed differentiation could be seen throughout the constructed portions of the field (Figure 5c). For group 4, one drawback of the construction was the manual doweling developed to accommodate for the curvature of the field. Once each manageable piece was completed the need to fully connect the full field together was needed, this was achieved by hanging each piece in its rough orientation on an existing hyperbolic net and then manually connecting each piece together (Figure 5d). With the use of high strength transparent wire the apparatus was suspended from the net, utilising the gusset plates as the main connection to the existing net condition.

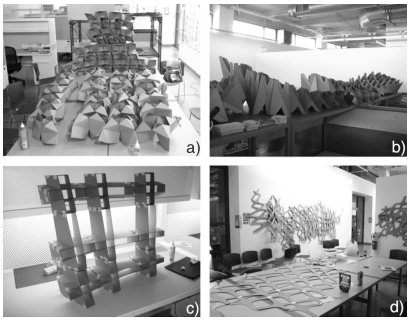

Figure 4. Construction Process: Each group project in various stages of assembly. Difference can be detected as the field continues to grow with the addition of each module component; a) Group 1; b) Group 2; c) Group 3; d) Group 4.

4.5. RESULTS AND ANALYSIS

For all four groups there were unforeseen failures. In all cases, the limitation of the 2-ply chipboard to carry its own self weight proved the greatest and most obvious failure. Every group experienced deformation and buckling in the walls of the bottom layers due to extensive amounts of stress upon the non-rigid 2-ply chipboard. Another second common cause for failure was the lack of simulation and anticipation of the tolerances and forces incurred

and needing to be managed in site. In other words the full implementations were not designed to accommodate real world deviations from a perfect Cartesian space. Although students understood the geometrical behaviour of the designed structure, lacking simulation of material and structural behaviour in the computational model led to these obvious failures similarly to work published by Menges (2007). Groups also were not able to easily update their design when needed due to individual components manufactured being vastly different from each other, once back in the scaled analogue the modules were no longer variable. Since each component in a parametric design has specific geometry, they cannot be merged into a new component and are not usable by other physical models (Sass 2009). In contrast to failures, a success for each student group was in the earlier paper prototyping stages and the development of structural depth, through curvature, folding and creasing, and joints and aggregation methods to garner structural rigidity.

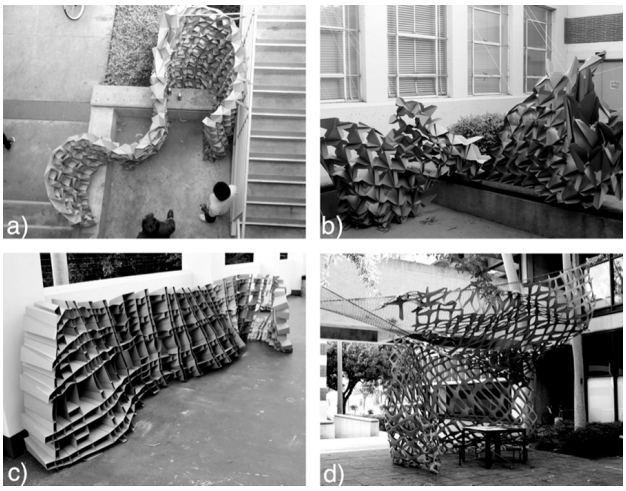

Figure 5. Final assembly, configuration:
a) Group 1; b) Group 2; c) Group 3; d) Group 4.

5. Conclusion

What began as a design study that borrowed from textile and fashion design for inspiring analogue card model unitisation and modularity quickly lead to questions of design iteration, and methods for translation into models for digital fabrication. Given the design intention for the designing and paper prototyping of fields of highly differentiated pattern the projects all arrived at a decision point of how to model digitally, how to incorporate parameters to ensure constructability and of how to tune for managing of continuously dif-

ferentiated modularity, albeit digitally. The teams individually began to move the prototypes into digital simulations and to model associatively and parametrically for means of control and design to fabrication.

A result of the analogue to digital back to analogue process was a realisation of materially based structural performance and the inadequacies of the pursued parametric methods. While the teams achieved successes in their design explorations and iterations, and in their ability to improve upon the control and direct communication to the digital fabrication the projects all suffered from a lack of resolution for incorporating the parameters of the material themselves. The complexity of the geometry was achieved but the encoding of the material stress, strain, and structural failure were not.

One pedagogic goal of the projects was to teach students parametric thinking through rapid prototyping. Rather than going directly from digital design and fabrication to analogue construction process, we intentionally promoted the students' hands-on form generation (or handcrafting) on paper to engage them in early 3D model development. As a result students began to anticipate the possible problems at a very early stage. They then represented and developed their analogue model in a parametric digital tool environment that helped them understand how to avoid design forms that are not manufacturable. The parametric modelling also helped groups to figure out the assembly process and fabrication sequence of their highly differentiated surface tiling. Students were able to observe the gap between computer representations and full-scale construction tangibly. CAD/CAM model translation and digital fabrication by precision laser cutting introduced students to the world of machining, shop drawings and proper cutting techniques. Students, however, were not given the opportunity to choose or search for a construction material. They were also not able to test their work before full-scale laser cutting due to limitations of class time. We believe material failures could be overcome through more prototyping and initial testing with their design.

Teaching through associative parametric methods also helped students' ability to create highly differentiated and fabricated geometries. Students were able to materialise their concepts from scratch and achieve learning by doing. The projects do contribute to the contemporary discourse of teaching through associative parametric methods in that they clearly demonstrate the capabilities and design methodology enhancements from the pedagogical and design research aspects, as seen through the vast amount of differentiated and fabricated geometries. Without the workshop and bringing to the teams the ability to parametrically and logically describe, and translate their ideas into a parametric design system the projects would have not achieved the degree of differentiation and the making of difference sought after. Here the notion

of PARA-Typing is an intentional neologism which speaks to the need for bringing associative parametric design technologies and methodologies to the studio problems as well as to the validated strength of the process, that of an increased solution space forming and by virtue an increase in materially pre-solved prototypes albeit partially form from which to choose.

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RATIONALISATION OF FREEFORM FAÇADES

A technique for uniform hexagonal panelling

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Abstract. This paper is an account of the façade rationalisation strategy developed at *Gehry Technologies* for mitigating the tradeoffs between project constructability and the aesthetic implications of arranging flat panels over a complex surface. The strategy outlined was developed as the result of the digital building delivery of the *Museo Soumaya* façade in Mexico City designed by Fernando Romero LAR. This report documents the development process of a method for obtaining relevant construction information flows enabling the assembly of the façade system by a third-party sub-contractor in support of the façade system coordination. This report concludes on a method using bespoke software for extending the parametric modelling system Digital Project™ in the design support role of obtaining an aesthetically pleasing arrangement of flat hexagonal panels over a freeform surface.

Keywords. Sphere packing; façade rationalisation; hexagonal tiling; parametric design; k-means clustering.

1. Rationalisation of unconventional forms

The execution of a conventional construction project is a reasonably low risk endeavour with readily accessible formulas for project cost control and time estimation, while on the contrary an unconventional construction project is subject to a high level of risk associated with the lack of well-known rules to support cost estimation and the challenges of quantifying non-Euclidean geometry (Shelden 2002).

Using a rationalisation strategy early in the planning of fabrication and assembly phases can potentially have a dramatic impact in reducing the increased cost and risks introduced with the use of unconventional geometry.

Fischer suggests the availability of different design rationalisation strategies for taking advantage of the fabrication economies gained with mass-production, as for example the rationalisation strategy employed in the *Beijing National Swimming Centre* allowed a reduction of the number of prefabricated unique building components in the assembly and simultaneously met the aesthetic goals of apparent irregularity (Fischer 2007). Fischer resurfaces three strategic opportunities in the rationalisation of unconventional forms originally presented by Hugh Whitehead, of the foster and partners *Specialist Modelling Group*; the three strategies deal with firstly the opportunities in decision making (pre-rationalisation), secondly how to cope with design consequences (post-rationalisation) and thirdly a hybrid strategy namely co-rationalisation where parallel decisions affecting the rationalisation of form can be made alongside the process of design.

This paper will demonstrate a façade rationalisation strategy developed at *Gehry Technologies* for mitigating the tradeoffs between project constructability and the aesthetic implications of arranging flat hexagonal panels over the unconventional geometry of the *Museo Soumaya* in visually pleasing arrangements. The rationalisation strategy had to manage the tradeoffs between a low number of unique building components and the effects these have over the perceivable irregularities of the panel-to-panel gaps (Fischer 2007).

2. Initial assumptions and rules

The façade rationalisation strategy of the *Museo Soumaya* was guided by a finite set of rules imposed by the design team as follows: 1) maintain a uniform gap between all six sides of the hexagon panel system; 2) begin with a standard hexagon size of dimension 63 cm diameter; 3) force the hexagon system to grow in scale (from a diameter range of 63 cm to 175 cm) as the pattern turns the corners of the façade; 4) group the panels into families, by minimising the amount of unique panels that need to be fabricated.

Parting from these rules, an addition of two important tactical design decisions guided the process of rationalisation, the first of these decisions opted in selecting early in the project a pre-rationalised turn-key solution patented by *Geometrica* for the fabrication of freeform space frame structures, the system would serve both as the panel positioning device and the support structure for both the aluminium panels and the waterproofing panels. The second decision was to freeze the MDS Master Design Surface as a fixed design component in the project; this is due to concurrent assembly processes within the interior of the project completing at a faster pace than that of the exterior façade engineering exercises, in order to avoid errors in misalignments further down the

construction process, the MDS was frozen, dimensions can be extracted from "slicing and dicing" the surface, although the MDS cannot be edited further.

As a design consequence of selecting *Geometrica*'s space frame strut and node system, the rationalisation strategy was reduced substantially, triangular configurations of same size circles produce hexagonal intersection patterns, each node in *Geometrica*'s space frame holds the centre of gravity of a single hexagonal panel and three incoming struts, forming a secondary triangular aluminium structure over the primary steel of the project providing support for hanging the outer aluminium panels and the inner waterproofing panels also developed by *Geometrica*.

The information requirements needed by *Geometrica* for the assembly of the secondary aluminium space frame using their proprietary system needed only the XYZ position and XYZ normals of each node in the assembly, as a result of a one to one relationship between the node and centre of gravity of the panels, obtaining a packing of panels over the surface and extracting the centre of gravity of the packing, provides sufficient information for coordinating the overall panel, strut and node assemblies.

In the following sections two unsuccessful rationalisation methods for obtaining the coordination data are examined, while the methods arrive at hexagonal packing's of panels over the MDS, they fail to address the design rules outlined in Section 2.

3. Conformal mappings

An often employed rationalisation strategy for obtaining panels over a doubly curved MDS is to roughly speaking wrap a 2D pattern drawing over the surface. In mathematical terms this operation is known as a conformal mapping. Depending on the results obtained, a mapping could exhibit two useful properties, firstly if the lengths in the original 2D drawing are preserved after transformation, the mapping is said to be isometric, and secondly if the angles between lines in the original 2D drawing are preserved after transformation, the mapping is said to be conformal.

The optimal solution to the rationalisation strategy would be a mapping that exhibits both isometric and conformal properties. In the case of the *Museo Soumaya* the MDS was defined as a NURBS surface digitised from a physical model. When wrapping 2D drawings over a NURBS surface, the mapping is neither length preserving nor angle preserving, unless the MDS is either a cylinder or a plane, in which case there is still the possibility of deformations in the conformal mappings due to the spacing of surface knots not being uniformly distributed over the surface.

4. Curvature gradients

Another traditional useful rationalisation strategy is to map the local Gaussian curvature properties onto the MDS, and from the mapping extracting the areas in the surface with relatively low curvature conditions, developable areas. Even though this approach allows wrapping 2D patterns over the Developable regions of the surface, the method cannot handle easily the transition between one area and its adjacent neighbour. Subdivision of the MDS by the Gaussian Curvature coefficient can prove to be useful in other panelling situations where a seamless panel distribution is not such a high aesthetical priority.

5. Circle hex meshes/sphere packing

This section presents the final successful rationalisation strategy employed for obtaining the panel, strut and node assembly coordination data for manufacturing and assembly. Intersecting circles produce the best hexagonal distributions in two dimensional spaces as shown in Figure 1, there is a one to one relation between the hexagon diameters and the circle diameters that produce them.

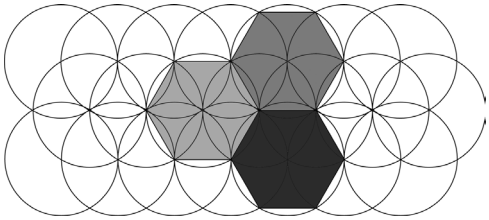

Figure 1. Hexagons enclosed by intersecting circles.

To control the diameter and the gap of the hexagon, we build a circle mesh of intersected circles, constructing the diameters of the circles from the values of the desired diameter plus the value of the desired gap, we suspend the actual hexagon by inscribing it on a circle offset inward using 1/2 of the desired gap as the offset value, a diagram of the extra wide circle and the suspended hexagon is shown on Figure 2.

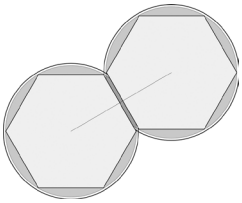

Figure 2. Hexagon diameter and gap.

Inspired from research on cellular aggregate structures, the intersection of circles and their inscribed hexagonal patterns resemble closely the formation of tissues or cellular aggregates in nature. Thompson (1961) modelled the morphological growth of cellular aggregates as the boundary conditions of intersecting spheres; Thompson (1961) identifies a "geometrical strategy" (Glymph et al. 2002) for reconstructing the emerging hexagonal patterns found in natural forms: "the four cells do not meet in a common centre, but each cell is in contact with two others, a so-called polar furrow, the visible edge of a vertical partition-wall, (joins or separates) the 2 triple contacts and so gives rise to a diamond shaped figure, identified more than a hundred years ago by Rusconi in a salamander and called by him a tetracitula." (Thompson 1961) In other words when two circles intersect they produce two intersection points as shown on the left in Figure 3 , if we draw a sphere on each of those two points we should arrive to the polar furrow configuration as indicated on the right in Figure 3.

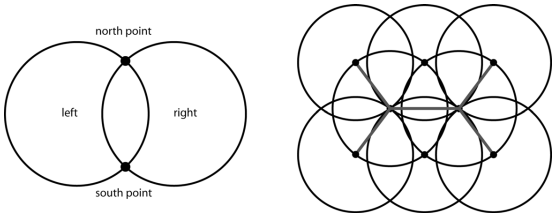

Figure 3. Polar furrow construction.

Following Thompson's insights of the polar furrow, we can construct any semi-hexagon as a local property of the intersection of two spheres with a doubly curved surface and then intersecting the two resultant curved circles supported on the surface and subsequently getting the north and south point, if we choose only the south point to locate another sphere and repeat this process until we have reached the end of the row, and then repeat the same process over and over again obtaining a new row for each pass, we can obtain a circle mesh grid over the surface as many rows and columns as needed see Figure 4 for the algorithmic process that creates the mesh, see Figure 4 for the result of the algorithm.

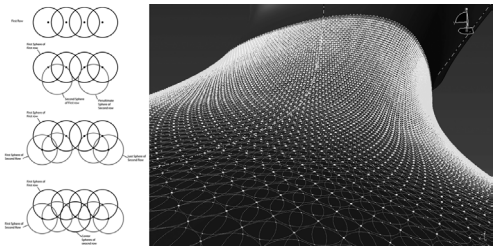

Figure 4. Sphere packing circle mesh grid.

From the circle mesh grid as pointed in Figure 4, the hexagonal pattern is extracted by hanging hexagons inscribed in an offset circle 1/2 of the desired gap.

6. Correcting stretching artefacts

Although the mesh is close to the desired result, the hexagonal mesh contracted vertically on the regions of high curvature and as a result the outer edge rose and retracted from the initial position due to the reduction in the height of the panels. In order to correct these artefacts, a post-production process must be executed over the resultant mesh to correct the height reduction; this process corrects the height of each panel from its current reduced height to the height of an ideal hexagon, which is a hexagon where each of its vertices has an interior angle of 60 degrees. The reduced height panels selected are shown on the left on Figure 5, and the result of correcting the panel heights is shown on the right in Figure 5.

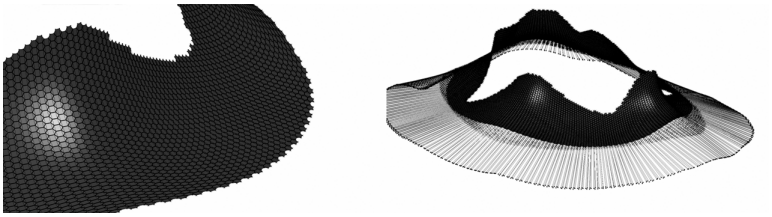

Figure 5. Custom panel skirt stretching process.

The process of correcting the heights of the panels requires first to identify all the panels that require correction. Passing a curve vertically through all the points in a column of panels, these curves are placed on top of the surface of the envelope and extended past the boundary edge of the surface, effectively these curves where used as rails to scroll the surface downwards until the vertical dimension of all hexagons corresponds to the horizontal dimension, there is a height to width proportion on a 60 degree hexagon, this ratio can be used to calculate the percentage needed to correct the vertical dimension of each hexagon. Before this process is executed, the panels that exhibit an abnormal squashing are filtered and selected as shown in Figure 6, the panels with abnormalities are referred to as custom panels and the ones with acceptable conditions are referred to as standard, Figure 7 shows the process of extracting rails from the panels and then stretching the panels over the extracted rails to correct their abnormality.

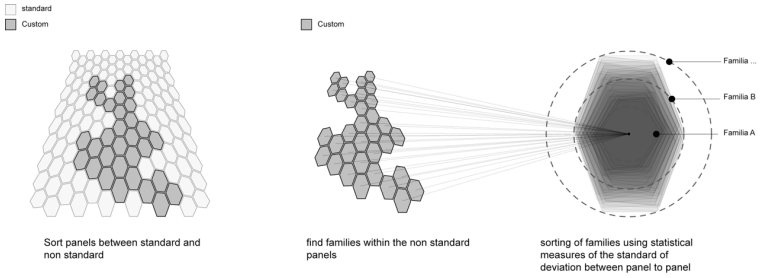

Figure 6. Panel family sorting process.

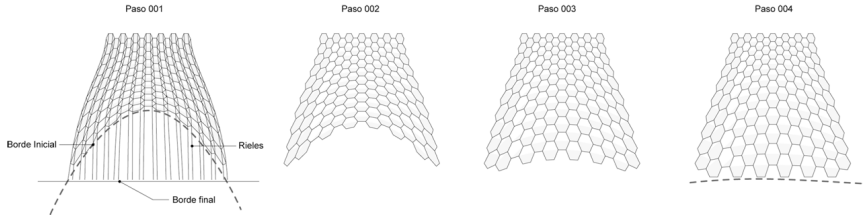

Figure 7. Panel stretching process.

The sphere packing and the hexagonal mesh extracted from it are sensitive to initial conditions, after conducting many trial and error studies, the pattern with the best aesthetics results were achieved by starting the sphere packing horizontally in the middle of the envelope. The location of the first sphere in the sphere packing algorithm has a high impact on the aesthetic output of the overall mesh, we found the most homogenous solutions where achieved by starting the sphere packing at a location on the surface with the least Gaussian curvature, to identify this location, an optimisation process was executed to identify this location, as shown in Figure 8.

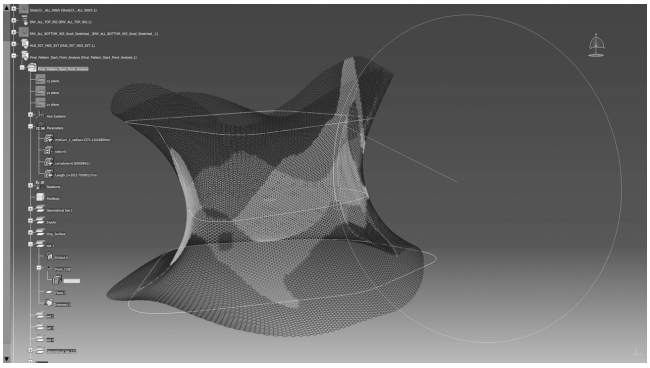

Figure 8. Optimisation process for finding the starting point of the pattern.

7. Clustering: reduction of unique building components

The client wanted to have only 7 or 24 unique type of panels within the overall mesh, this is due to the cost of producing a single mould, and a personal fixation with the numbers above, the challenge was to maintain a pattern that would keep the family as strands from the middle of the façade waving outward in both directions.

By executing a statistical k-means clustering analysis over the panel population using 21 parameters as attributes and weighing the Area of the panel as the key attribute, the clustering analysis yielded the result wanted.

Given the area in the middle zone is the closest to a cylinder and the panels seem to stretch as they move away from the middle band, the striation effect in the resultant families was achieved almost naturally as shown on Figure 9. The inclusion of the area in the calculation of the clustering analysis is crucial to achieving the banding effect over the distribution of the families. If instead the area is omitted in the calculation, a more patchwork distribution is achieved, the patchwork distribution is more faithful to the original geometry, although it increases the logistics of fabrication, as there would be more fragmentation over the distribution requiring the use of schedules for the location of each panel, in contrast with the striation, only the boundaries of the families need to be identified and all the panels inside the boundary can be safely placed knowing they correspond to that particular family, this is convenient to employ when the assembly is carried out by unskilled labour, while minimising construction errors.

The k-means clustering process is outsourced to excel using a statistical plug-in for the k-means clustering function, each panel was exported as an instance with 21 parameters measuring intrinsic properties of each panel, these properties are internally compared to one another, in order to determine how to sort the panels into the fix number of families.

The K-Means cluster analysis starts with a setup function that is executed once at the beginning to seed the process, in this setup function the algorithm creates k number of families, and then iterates over the list of panels assigning randomly a family to each panel.

The algorithm then recursively runs the following pseudo code until it converges. Convergence in this case means until no panel needs to be reassigned to its nearest family:

1 – For each family in a list of families with k number of families,

1a – Find the Centroid of each family.

Centroid: defines the best panel representing the family.

2 – For each panel reassign to the family with the closest Centroid.

3 – Repeat Step 1 and Step 2 until convergence.

Depending on which parameters are given as attributes of the panels for cluster analysis the results of the clustering produce different results, Figure 9 shows the differences between omission or inclusion of the panel area, as well as increasing the number of families, both affecting the fragmentation of the resultant clusters as well as the pattern continuity.

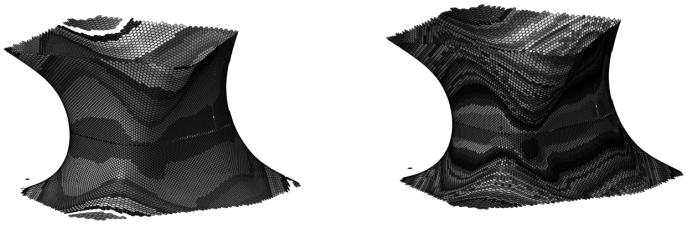

Figure 9. Left: 7 families with area, right: 49 families without area.

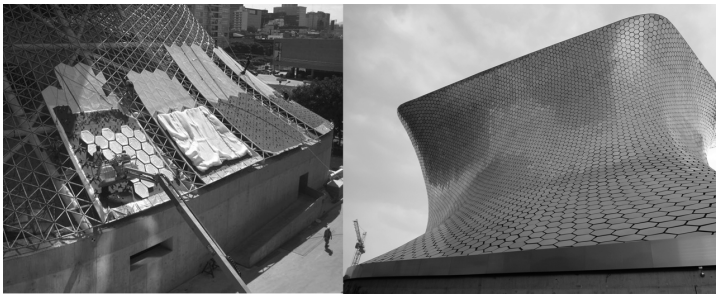

Figure 10. Left: Installation Process, right: Finished façade.

8. Conclusions

This report outlines various rationalisation strategies for negotiating tradeoffs between geometrical and aesthetical implications.

The most successful rationalisation strategy found the most aesthetically pleasing distribution of panels by using a stable sphere packing method, and a self-adjusting pattern stretching algorithm, by extending Digital Project™ through bespoke software solutions.

A solution to cataloguing the resultant panels was found using a straightforward approach involving the use of a k-means algorithm for the clustering process in Excel™ and the subsequent mapping process for returning the result into Digital Project™, by using a k-means algorithm as opposed to a hierarchical agglomerative clustering algorithm, an approximate solution was found at a faster time, while giving the user control to specify directly the exact number of families desired.

Acknowledgements

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ENVELOPE TESSELATION WITH STOCHASTIC ROTATION OF 4-FOLD PENTTILES

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Abstract. The challenge of developing adaptive, responsive low-energy architecture requires new knowledge about the complex and dynamic interaction between envelope architecture and optimisation between competing environmental performance metrics. Advances in modelling the geometry of building envelopes and control technologies for adaptive buildings now permit the sophisticated evaluation of alternative envelope configurations for a set of performance criteria. This paper reports on a study of the parametric control of a building envelope based on moveable façade components, acting as a shading device to reduce thermal gain within the building. This is investigated using a novel pentagonal tiling strategy considering the component design, tessellation and control methods.

Keywords. Responsive envelopes; moveable façade components; parametric modelling; tiling geometry; stochastic rotation.

1. Introduction

The challenge of developing adaptive, responsive low-energy architecture requires new knowledge about the complex and dynamic interaction between envelope geometry and optimisation of performance metrics. In this paper, we present the results of a building envelope tessellation study based on façade components with rotation. The rotation methods are based on stochastic rotation of panels, primarily responding as a shading device to reduce thermal gain within the building.

This paper reports on the geometry and control aspects of façade subdivision using 4-fold penttiles (also called Cairo pentagonal tiling), a dual semi-regular tiling of the Euclidean plane. The penttile method (Hanafin et al. 2011) is used to define the façade pattern and its subdivision into discrete components.

2. Background

New advances in the geometric representation of envelopes (Pottman et al. 2007), new construction materials (Schittich 2005) and control technologies for adaptive buildings combined with advances in the field of design space exploration (Woodbury et al. 1999, Aish and Woodbury 2005, Datta 2006, Woodbury 2010) now permit the sophisticated evaluation of alternative designs for a set of performance criteria (Radford and Gero 1988).

However, current models lack the ability to handle envelopes of variable geometry (Kolarevic and Malkawi 2006) and do not account for local variations in climate conditions (Guan et al. 2007). These models also do not include multi-skin façades (Saelens et al. 2008). Tools that calculate the performance requirements (solar gain, daylight penetration, heating and cooling loads, ventilation, water use) of a building (Shaviv 1999, Malkawi 2004) require an extensible geometric representation (Malkawi 2006). It is anticipated that rapid, near real-time visual output from such representations would significantly improve the prediction of performance and enable the optimisation of smart, adaptable, net zero energy buildings (Hensen and Augenbroe 2004). To address these limitations in a unified way, this paper reports on developing a responsive envelope based on the tessellation of 4-fold penttiles. Further, it addresses the problem of responsiveness to multiple criteria by applying a stochastic method (Datta et al. 2009) for the rotation of individual panels (Hanafin et al. 2011).

3. Problem statement

To motivate the discussion, of a responsive building envelope, we based our study on the façade design of the “pixel” building in Melbourne. The building was designed with the goal of being a carbon neutral office building and to be used as a prototype for sustainable and environmental buildings. The façade is one of the devices used in the building to reduce its environmental impact.

The façade involves a series of ‘jumbled’ coloured and textured panels that act as an aesthetic to the building façade and as a shading device to reduce thermal gain within the building. Each panel is designed to be positioned and angled in a fixed location based on optimal shading in the Melbourne climate.

Panels will not only reflect or absorb the sun, but also allow views out from the building with perforation and transparency in the materials. In order to further optimise performance, the problem of component motion with respect to changing conditions needs to be addressed. To address this problem, we initially developed the façade subdivision scheme from first principles to investigate its responsiveness to environmental conditions and presented our findings in Hanafin et al. (2011).

Further to this analysis, the stochastic rotation of the south façade of the pixel building was undertaken in order to facilitate understanding the shapes and rules which determine the façade composition. This elevation consisted of jumbled panel façade and precast panels with the cast patterns (Figure 1). The tiling used on the elevations is identified as a Cairo pentagonal tiling, which is a type of polygonal isohedral types of tiling by pentagons (Grünbaum and Shephard 1987).

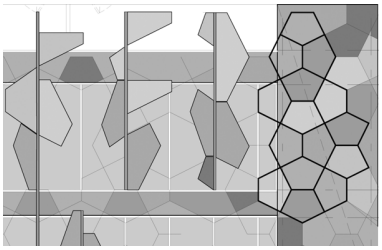

Figure 1. South elevation with Cairo tiling overlaid (source: VDM Consulting).

4. Multiple support method

The Cairo tiling is classified as a regular tiling (each pentagon is identical), However, as the orientation of each pentagon changes, this presents issues with surface-component application in conventional parametric modelling tools. With this in mind, a multiple support method is described that generates an underlying support structure, allowing for the orientation property of four individual pentagons to be applied correctly.

4.1. COMPONENT DESIGN

The geometry of the initial pentagon has a bounding box dimension of 1200 by 900 and a spacing of 1500, which does not replicate into a uniform surface grid (Figure 2). In order to correct this, the overall component needs to be developed to replicate within a uniform surface grid. If the surface grid is developed using the pentagon's width, 1200, the replication becomes more manageable and simply requires control over the positioning of the pentagon within the grid. In order to ensure this correct placement, a spacer is used at

the apex of the pentagon which results in the overall bounding box dimensions of the component being 1200 by 1200.

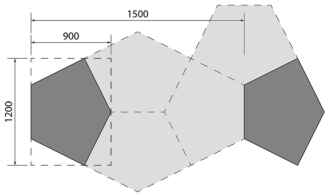

Figure 2. Cairo tiling, Pentagon shape and offset.

4.2. TESSELLATION METHOD

The first step in developing the overall tiling is to establish the surface geometry of a single vertical set of tiles, beginning with the bottom pentagon from the hexagonal collection. A horizontal line was created based on the width of the tile unit. From the start and end points of this line, two vertical lines were created with an initial length of 14.4 m. Between the two vertical lines a base surface could now be generated. The base surface was then subdivided using its U and V parameters. In the case of the U parameter is one as this surface carries a single set of vertical tiles.

With the first supporting surface established, three more are required and can be achieved by offsetting the first. Moving in a clockwise direction the offsetting can be undertaken (Figure 3, Left) by adjusting the start point of the baseline from 0, 0, 0 to: –0.6, 0, 0.6 (left); 0, 0, 0 (top); 0.6, 0, 0.6 (right).

When the component is applied to the supporting surfaces, a pentagon is generated in each of the polygons resulting in multiple pentagons that overlap. Using a data list method, the excess tiles are culled, leaving the desired pattern. The cull function uses a true-false pattern allowing for the desired tiles to be maintained, removing the overlap and producing the Cairo tile (Figure 3, right). With one vertical section complete, offset sections are now required which will allow for a complete façade to be produced. A position count variable is used to achieve this, which influences all four pentagons in a set.

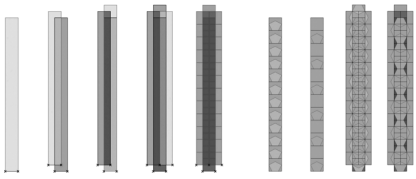

Figure 3. Left Set: Offsetting of the support surfaces and subdivision.
Right Set: Culling of the pentagons to produce the Cairo tiling.

4.3. CONTROL METHOD

With the façade tiling established, the rotation of the individual tiles requires an axis for rotation defined by two attributes, centre point of the base horizontal line and the depth of the component.

The tile data list is used to establish a collection of random values to rotate the tiles producing a "jumbled" pattern. A pseudo random generator was developed that could provide rotation information to all four sets of pentagons within a vertical set with a seed input and range of values. The seed input is influenced by the position count of the tile set, so that each vertical collection will receive a different seed input. The range of values is treated as the minimum and maximum rotational angle in degrees and is adjustable, so that this can be tuned.

The list of values is processed in order to give the rotation information to each set of pentagons individually. This process is repeated producing four lists of rotational inputs that match the size of the original pentagon counts. These lists can then be input to the rotational tool, generating a randomly rotated collection of pentagons (Figure 4).

The multiple support tiling method successfully produces the Cairo tiling but various shortcomings exist. The need to predetermine the overall area of tiling required makes this model very rigid, and requires repetition and manual adjustments to establish the finished tiling. In order to allow for a more flexible and intelligent application of the Cairo tile, a single surface method for envelope tessellation with stochastic rotation is developed.

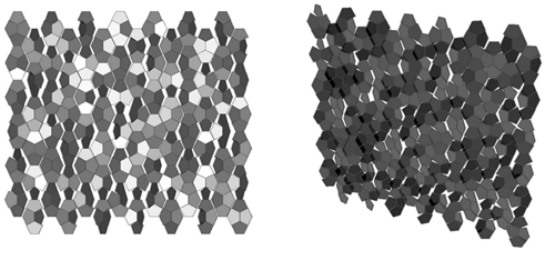

Figure 4. Panel rotation based on stochastic data list.

5. Single surface method

The starting point for the new method is a single surface. This removes the limitations evident in the vertical collections and allowing the overall surface to be changed with the tiling being regenerated automatically. While this approach allows more flexibility, it present more issues in the management and control of both the base surface and component application.

5.1. COMPONENT DESIGN

The pentagonal geometry of the tessellation tiling is extended with two extra inputs, a rotation point for orientation and a tile rotation parameter. Consider the two pentagons, an initial one and its mirrored version as shown in figure 5. When placed within the same surface grid cell it can be seen that there bottom edges are on opposite sides of the cell. The pentagons are grouped into two sets, vertical and horizontal, using the point of rotation as defined in the base component. The point of rotation is placed 2/3 along the tile height to ensure the correct placement of the pentagon within the surface grid. By adding the rotation axis parameter, the each tile is able to rotate from the bottom of the pentagon regardless of its application orientation.

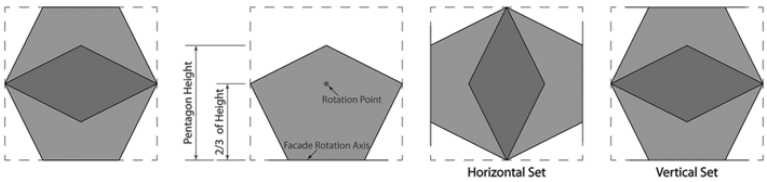

Figure 5. Overlapping mirrored pentagons, Base component with pentagon, rotation point and rotation axis, Horizontal and Vertical sets.

5.2. TESSELLATION METHOD

This method takes a predefined overall surface and applied two sets, the horizontal pentagons and the vertical pentagons to create the envelope tessellation.

The first step in the horizontal application is to take the dimensions of the surface and divide it by a predetermined tile size, this number is converted to an integer to allow for a clean surface grid to be generated as close to the preferred tile size as possible. With a surface grid established the horizontal component is applied, which at contains two overlapping pentagons and each of their rotation axes. In order to achieve the Cairo tiling, the pentagons need to be culled. The culling process is developed as two vertical sets (columns), as two patterns exist within the overall tiling (Figure 6).

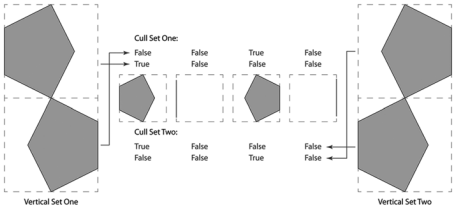

Figure 6. Cull set patterns.

Each vertical cull set is then multiplied by half of a vertical tile count of the surface in order to generate a full list for each vertical set, which is then combined and used as a loop to cull the pentagon set and provide the required pattern (Figure 7, left).

In order to apply the vertical pentagons the surface needs to be redeveloped, as the vertical pentagons grid is offset from the horizontal and in order to contain all the pentagons within the initial surface. The surface is analysed to obtain the actual tile width and height. This allows for two vectors to be established, a positive vector (upwards and to the right) and a negative vector (downwards and to the left). Using the positive vector, a copy of the surface is made and the resulting region intersection calculated. This resulting surface is then copied by the negative vector and the resulting region intersection of these two surfaces is calculated, giving a final surface that has been trimmed by half the actual tile width and height.

As with the horizontal pentagons the surface is then subdivided to allow the vertical component to be applied, follow by a cull process (Figure 7, middle). The cull pattern required for the vertical tiles is based around the first two tiles of the application resulting in the same pattern as cull set one.

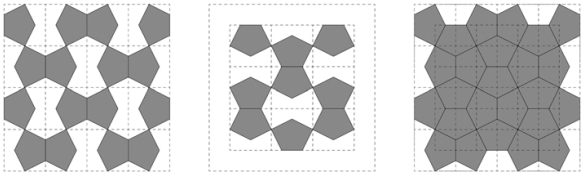

Figure 7. Left: Horizontal tile cull, Middle: Vertical tile cull, Right: Complete tiling.

5.3. CONTROL METHOD

A data set of rotation axes and a data set of tiles allows for the control of the façade to be managed. Rotation information can be developed based on both aesthetical requirements, such as the ‘jumbled’ pattern, and environmental benefits, such as shading and views.

In order to calculate environmental conditions information is required from both the tile, in the form of a direction vector (tile orientation), and the environment, in the form of an attractor point. A vector is established between each tile and the attractor point allowing for the angle to be calculated between this vector and the tile direction vector. This data set of angles is processed to meet the requirements of either shading or views, and provides the rotation information to each tile. Multiple environmental attractor points can be calculated and optimised based on the desired performance metrics. Both the

horizontal and vertical tiles can be developed using the same environmental conditions, or managed as separate sets to meet different requirements.

While this information reacts to environmental conditions, the 'jumbled' pattern is lost due to the uniform nature of using attractor points. In order to achieve a balance between the two requirements a pseudo random generator is used to produce a set of values. These values are then combined with the calculated environmental values in order to provide the final rotational information to the panels.

6. Results

This paper reports on a comparative study of two formal methods for generating responsive envelope tessellation based on the Cairo tiling. The façade schemes investigated alternate component design, tessellation and control methods. The results of these tests are presented here.

The outcomes of the responsive exploration were a flexible façade geometry based on tiling and tessellation, creating order and rhythm within the façade. In order to achieve the desired pattern, the tessellation and control methods become more critical than the tile itself, allowing for the control of the tiles both individually and as a group. This control can be based on stochastic models, allowing for the pattern and rhythm of the tiling to be explored within set parameters and achieve unexpected results. The control can also be very strict and focused, taking advantage of attractor points representing environmental characteristics. The paper presents a new method for supporting tessellation with Cairo tiling. This method addresses the limitations evident in the vertical collections and allowing the overall surface to be changed with the tiling being regenerated automatically. The study is limited in terms of its focus on the geometric control aspects of the representation scheme. Further analysis of the methods incorporating performance metrics derived from local climate variables, material constraints, structural and load considerations, clash detection within the rotational controls and automated control using networked sensors are currently under investigation.

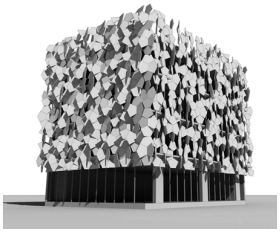

Figure 8. Cairo tile façade visualisation.

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3B PRACTISE-BASED AND INTERDISCIPLINARY DESIGN I

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SOME ADVICE FOR MIGRATING TO IFC

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Abstract. Nowadays, the BIM (Building Information Modelling) paradigm is a central topic in the CAAD community. Next to the commercial solutions, the IFC (Industry Foundation Classes) have emerged as the best open standard candidate for BIM interoperability. Despite the efforts of the community for promoting IFC over the last 15 years, it seems that its practical adoption in real-life projects has been very limited. The goal of this article is to explore how useful IFC can be today and to provide the reader with some advice for an effective adoption of IFC. Over the last year, we have conducted a project aiming at acquiring a sound understanding of IFC. It was made of two complementary investigations. On one hand, we have focused on the commercial modelling tools and the IFC support they were offering. On the other hand, we have focused on the IFC-based software developments. We have developed a tool converting IFC files into a dedicated thermal assessment based model. We will summarise the experience we have acquired in this project into some advice for users migrating to IFC. Our goal is to confront the practical aspects of the IFC developments, with both the theoretical ambitions and the commercial support currently available.

Keywords. Building information modelling; industry foundation classes; interoperability.

1. Introduction

The building design process has to be improved to face the new challenges for building at the 21st century: managing increasingly complex buildings, ensuring high standards of comfort and security or controlling the energy consumption of buildings.

To do this, it is necessary to predict accurately as early as possible the performances of the building taking into account the entire life cycle: design,

construction operation and demolition. We have for this simulation software more and more efficient. However these software requires accurate information about the building: technology, material properties, measurements etc. Therefore they need a building model they can query to extract these data. One paradigm being put forward to address this issue is the Building Information Modelling (Eastman et al. 2011).

1.1. BUILDING INFORMATION MODELLING

Following the definition of (Ashrae 2009), the ambition of BIM is "to capture both physical and functional aspects of the building in order to generate an accurate model that is useful throughout the entire life of the building, from initial design through occupancy and operation". Archicad from Graphisoft or Revit from Autodesk are examples of BIM software. Next to the commercial solutions, the IFC (Industry Foundation Classes) has emerged as the best open standard candidate for BIM interoperability (Liebich et al. 2011).

Benefits of BIM adoption are numerous, both quantitative and qualitative (Azhar et al. 2008). However, despite the efforts of the community for promoting IFC over the last 15 years, it seems that its practical adoption in real-life projects has been limited. Reasons are both technological and sociological or organisational (Coates et al. 2010, Deutsch 2011).

The goal of this article is very pragmatic. It is to explore how effective IFC can be today and to provide the reader with some advice for an effective adoption of IFC.

1.2. CONTEXT

Over the last year, we have conducted a project aiming at acquiring a sound understanding of IFC. It was made of two complementary investigations. On one hand, we have focused on the commercial modelling tools (mainly Revit and ArchiCAD) and the IFC support they were offering. We have analysed which kind of IFC features they were supporting and how well interoperability was working between these tools.

On the other hand, we have focused on the IFC-based software developments. We have developed a tool converting IFC projects into models for PEB (Energy Performance for Building, the format for the Belgian regulatory tool for the thermal assessment). The re-encoding of a building in PEB is a time-consuming task. Being able to import IFC directly is a timesaving feature. We believe that these kinds of functionalities would greatly enhance the adoption of IFC by providing direct benefits to the users switching to this technology.

We will summarise the experience we have acquired in this project into some advice for users starting with IFC.

There are many examples of the use of IFC to assess the performance of buildings. It is clear however, that when trying to exchange data between commercial software via IFC files, the results are often disappointing. On the other hand, the scientific literature abounds with examples of use of IFC for building assessment. For example, in the area we are interested in, Verstraeten et al. (2008, 2011) use IFC data to feed the thermal and acoustic regulation software provided by the Flemish government. However, these researches are usually more proofs of concept than feasibility study in real life projects. Our goal on the contrary is to confront the practical aspects of the IFC developments, with both the theoretical ambitions and the commercial support currently available.

2. IFC and modelling strategies

We have developed a tool converting IFC files into a geometric format adapted to the Belgian PEB software. But before obtaining the IFC file, the geometry and thermal properties have to be encoded in a commercial BIM software. In this section, we focus on the modelling strategies that have to be adopted to export valid IFC files.

Schematically, the PEB thermal model is composed of volumes characterised by climatic data (temperature, occupancy, ventilation rate) separated by walls characterised by thermal properties (heat transfer coefficient, thermal inertia). All these data can be included in a IFC file by the property set mechanism.

The figure below illustrates our work. It shows a BIM model built in ArchiCAD version 13 (Figure a1 and b1) and exported in IFC. The IFC structure has been validated in the Solibri IFC viewer tool (2012) (Figure a2 and b2). It has then been processed and converted into the PEB format (Figure a3 and b3).

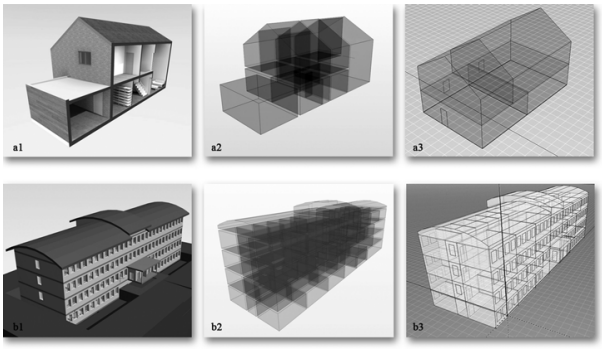

Figure 1. From Archicad® to the PEB energy assessment software.

This model-driven approach has brought to light a few issues related with some very specific and advanced modelling functions within traditional modelling tools.

The resulting IFC files were different than what the user could see in their CAD software. These problems were not due to the IFC format itself, but to the lack of maturity of the IFC support of the CAD tools.

The BIM software produces a geometrical model that is visually correct. But during the IFC export, some of the geometrical information is wrongly translated, leading to an incorrect IFC model.

To illustrate this, we will detail two examples with two well known architectural software. We will focus on the modelling aspects of the junctions between walls and their upper frontiers. The first example is based on Revit Architecture from (Autodesk). To reach a complete BIM model, one has to define the different structural elements of the building, the envelope and its properties, the openings, the thermal volumes and other miscellaneous information. One problem appeared while defining the thermal zones. Revit offers an efficient tool to do so, but this information gets lost during the IFC export. The software automatically detects the 2D frontiers of a plan, but the user has to manually adjust the height of the volume, in a way to cross the top boundary of the building. The software will automatically computes the intersection of the volume and the top elements and removed any exceeding parts of the newly defined volume. Unfortunately, this correct result gets corrupted during the IFC export. The profiled space boundaries don't make their way into IFC. Instead, we see the boundaries of the uncut initial volume. When we get a correct visual representation of the thermal zone in Revit (Figure 2a,b), its space boundaries in IFC are geometrically incorrect (Figure 2c).

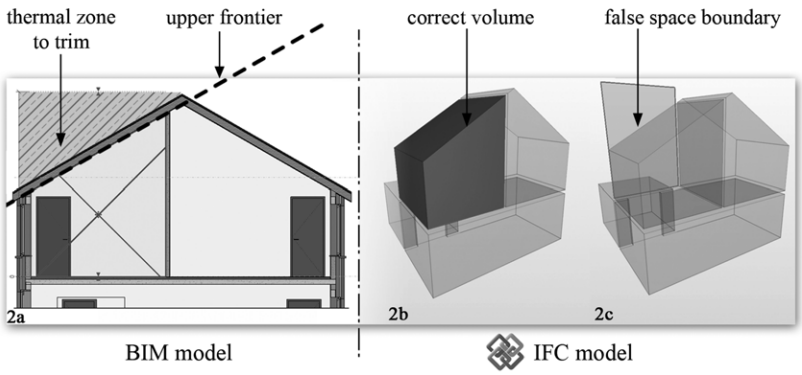

Figure 2. Thermal volume defined in Revit Architecture® and its IFC export.

The second example is based on ArchiCAD from Graphisoft (version 15). It appears with some "dynamic" tools, like "trim/join wall to roof". The specificity of these tools is that it maintains the declared relationship even if you move one of the components afterwards. Here again, the visual result is correct. But the geometry exported in IFC does not match the operation. We lose the joining/trimming result and only get the initial components of the operations.

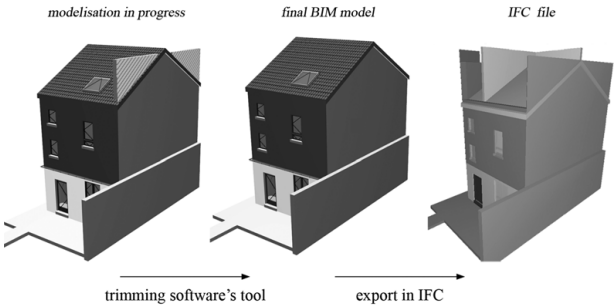

Figure 3. Archicad® trimming tool and its IFC export.

Without any further checking, you might end up with an IFC document providing you with false information, like surface estimations, etc. The solution here is to avoid using these dynamic tools, and instead use classical Boolean subtraction operations. This generates a correct IFC model. However these operations are hardly reversible in case of future modification.

These different examples should not stop you from trying to use IFC in your projects. The encountered problems are due to a lack of maturity in the supporting tools, and this should be improved in the next versions of the software (the new ArchiCAD release already offers an extended support of IFC over the previous version).

Still, we advise you to evaluate the IFC result you get on a "per design tool" basis, before adopting it in your projects. That way, you should be able to know which tool subset in your CAD software is fully IFC compliant, thus preventing you from any bad surprise during your project phase.

3. Developing for IFC

IFC is an extensive data schema, formally described with the STEP representation. Most of the documentation you can find today about the IFC format will be low-level, closely following its STEP notation. The BuildingSmart website (2012) might be the best place to start with. It contains an exhaustive description of all the IFC classes with some helpful information on how to

interpret the different fields and relationship. For example, you can find the description of the IfcSpace here[1].

Despite this important source of information, it requires a long time to get accustomed to the IFC model. The reasons for this come from two combined and very valid design choices described below.

Firstly, IFC relies a lot on inheritance. For instance, IfcWallStandard-Case, the most common wall representation in IFC, is at the bottom of a long inheritance chain of 7 parents. This causes some learning overhead, as other classes might have inexplicit links to IfcWallStandardCase through any of these ancestors.

Secondly, in IFC, relationships are first class objects, which is a powerful way of decoupling the elements and their relationships. It also allows for properties to be stored in the relationship. But this increases the learning curve, as one must browse that many classes in order to understand how some specific elements are bound together.

We want to emphasise that these design choices are perfectly valid and are sound decisions. They also prove to be useful once one has some experience with the format. Still, as far as the initial learning is concerned, these characteristics makes it very difficult to understand how objects are linked together without further documentation than the low level IFC description.

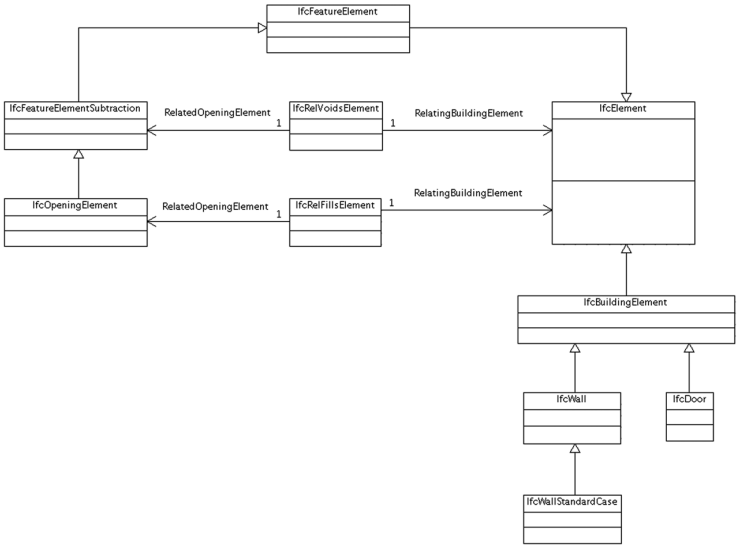

Figure 4. Class diagram for the relationships between a wall and a door.

1 http://buildingsmart-tech.org/ifc/IFC2x4/rc1/html/ifcproductextension/lexical/ifcspace.htm.

The following example will illustrate this (see Figure 4). It shows the class diagram for the relationships between a Wall and a Door. In IFC, both of these elements inherit from IfcElement. There is no direct relationship between a wall and a door. Instead, an IfcElement can be linked to an IfcFeatureElementSubtraction through an IfcRelVoidsElement. An IfcOpening is of type IfcFeatureElementSubtraction, and can be linked to another IfcElement, like a door, through an IfcRelFillsElement.

After some thoughts, this makes much sense, but documentation is lacking about this, so you have to figure out this schema from reading on all the description of these different classes.

Instead of trying to figure out the IFC format by reading its class descriptions only, we advise you to work with an 'object diagram' approach. The strategy is to model a simple example of the elements and relationships you want to study in an IFC compliant modelling tool, to export its IFC file, and to reverse engineer the given document. Indeed, if you consider only the 'concrete' objects, the wall-door relationship will look like the following figure which is far easier to understand:

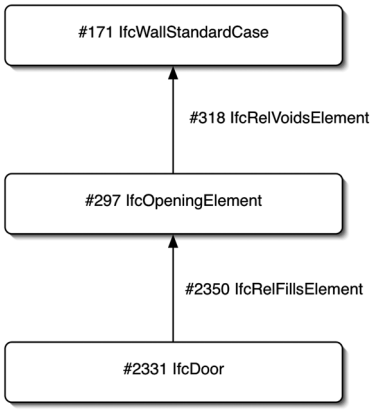

Figure 5. Objects graph for the relationships between a wall and a door.

Our developments were made in Java. We have relied on the Open IFC Java Toolbox library (2012), a convenient library to parse and access IFC documents. We have developed a small tool able to display whatever selected element types we are interested in, and all or some of the relationships linking these elements. With this tool, we can see how concrete objects are linked. By focusing only on concrete objects, we bypass the heavy hierarchy of IFC, and by displaying all the relationships, we do not have to study the exact semantic of the IFC relations. Once we have learnt enough "by example" with

our object diagrams, you can go back to the classes documentation and easily reconstruct the above class diagram.

This approach has started to be adopted in the IFC world, and you will find more object diagrams in the building smart documentation of IFC 2.4 than in the documentation of version 2.3.

4. Conclusion

IFC is a lot more than the few elements considered in this article. The format addresses products, processes, resources and contexts. In this research, we have focused on some of the core aspects of IFC: a few of the main products and their geometries.

Considering the vast ambition of IFC and the many issues such an interoperable file format might encounter, we didn't know how good IFC would be to cope with the few challenges considered in our evaluation.

At first, we have suffered from the lack of a high level documentation and from some modelling issues in the commercial offer. When these critics are nothing fundamental about IFC, they may seriously limit the adoption of the technology by newcomers. We have tried to provide the reader with some useful strategies to work around these few problems, in order to speed up the initial learning phase of IFC. Also, the recent progress in both the norm description and the modelling tools have brought some improvement on these problems.

After some time playing with IFC, we could take advantage of the format and get some real benefits from it. We were able to read IFC from a couple of different modellers and convert it into a dedicated thermal assessment format. So IFC has correctly fulfilled its interoperable mission within this project.

After these first conclusive tests, we have also evaluated the export of IFC files in another project of ours, where a dedicated modeller was being built. In this context, the results were excellent: we were able to export our BIM project into most of the main commercial modelling tools, opening our software with limited analysis capabilities to a whole new range of features available in external applications. On both the modelling and development side of our study, we have found that IFC was able to cope with today's challenges, at the cost of an adapted modelling/developing strategy requiring some time for learning and evaluating the technology.

Acknowledgements

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AN IFC BASED DESIGN CHECK APPROACH FOR THE OPTIMISATION OF MATERIAL EFFICIENCY IN THE BUILT ENVIRONMENT

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Abstract. Compared to other industries, the built environment is still the largest and one of the least efficient consumers of resources. Existing measures and procedures for resource recovery and reuse are focused on the demolition phase, when the composition of materials and structures is mostly unknown and hard to be analysed. Therefore, these measures are somewhat inefficient for overall high-rate material recovery. The enhancement of the integrated semantic planning process by the introduction of the IFC unified data standard and BIM technology is a first-time opportunity to track, analyse, document and simulate all relevant players, parameters and processes with an impact on the resource and material efficiency through the entire life cycle of a building in the design phase of a building project. The presented work explores the potential of IFC to serve as a framework for achieving a higher material efficiency in the built environment. A proposed design check approach for the simulation and optimisation of material efficiency in a building over its life cycle is based on a system of key parameters and actions organised in logic trees. The parameters and actions are translated into IFC objects. Additionally required IFC objects and properties are identified and described.

Keywords. BIM; IFC; integrative design; material efficiency design.

1. Introduction

Unlike the majority of the manufacturing industries, the construction industry is one of the very few still missing a systematic design approach to react to global environmental, economic and social trends in the context of uprising resource shortage. Recent studies confirm that the built environment is the

greatest consumer of resources (50%) and energy (40%), producer of greenhouse gases (40%) and land de-aggregation (70%) (IEA 2009). Due to the systematic implementation of Design for X (DfX) approaches in the last decades, industries such as the automotive or the electronics industry have achieved nearly closed material cycles by enabling high reuse-rates and minimising material resource losses over the product life cycle as well as the demand of raw materials input (Shu and Flowers 1999, Toyota Motor Marketing Europe 2001).

This paper presents the first two steps of a research project, the aim of which is to propose a concept for the closing of material cycles in the built environment. The concept is based on the principle of the integrated design process, utilising the unified data standard IFC (Industry Foundation Classes) and current BIM (Building Information Modelling) software as a platform. Its first phase consists of the following steps: a) a direct confrontation of the building design process with best practices from high-performing industries in terms of material resource efficiency, dealing with the specifics and deficits of the construction process with regard to the implementation of an integrated design check approach and b) the development of an analytical model, consisting of concrete design parameters, measures and processes linked in logic trees as well as the translation of the key values into IFC objects.

2. Car design vs. building design

Currently, the automotive industry achieves a recovery and recycling rate of 85 weight % and 5% energy recovery from end-of-life vehicles with a target of 95 weight % and 10% energy recovery for 2015 as a result from a systematical integration of Design for X approaches in the design phase (Toyota 2001). The measures considered in these approaches are focused on the restricted use of compound materials in correlation with the choice of connections for components and elements in the product to increase recycling, recovery and reuse rates and decrease the disassembly time and sequences. Basic requirements for the practical applicability are: a) the integrated planning process in which all actors over the product life cycle are participating, b) the explicit implementation of DfX methodologies focused on material efficiency in the product design phase and c) the legislation, which is the crucial requirement for a wide implication of these approaches in practice.

As stated above, the construction industry is significantly less efficient. The reasons for this discrepancy are complex. Among others, these are: a) the uniqueness and high complexity of buildings compared to products of other manufacturing industries, which is a significant barrier for the introduction of standardised design approaches; b) the extremely long life time of buildings

compared to other products, which means that designers lack the possibility of empirical feedback on the design performance over the whole life cycle; and c) the standardised building design process, which is based on strictly split design activities among the parties, often performed in different data standards and IT systems. These reasons are widely recognised as a fundamental weakness for the introduction of integrated, interdisciplinary design approaches in the construction industry (Austin et al. 1999).

3. The analytical building model

The proposed analytical building model has two main objectives: It provides the structure for a substance and material map, which documents the location of materials and their properties (physical properties like material type or density, but also analytical properties like recyclability or composition). Furthermore, it supports the identification of process and parameter intersections, where optimisation, data input or design assessment are possible or needed.

The proposed functional area division originates from three main considerations towards material management over the life cycle of a building: First, elements and products that have the same function can be linked into groups with identical or similar physical properties, which could enable material and structural aggregations and/or optimisations during the building design process. Second, elements with the same function often have similar life durations. Thus, there is a strong correlation between their respective times of disassembly as well as the possible recycling of their materials and their return into the built environment material cycles. Third, designers have to be able to make detailed changes to the physical and material efficiency related properties of elements and structures. This is highly available where design teams decide over all parameters of a building element (geometry, constraints, materials etc.) and significantly restricted where they rely on pre-manufactured products. Therefore, the building model map is divided into two main branches: “designed in project” and “pre-manufactured” (see Figure 1). Accordingly, in the map the term “building element” describes elements completely designed by the design team while the term “building product” refers to pre-manufactured building elements.

Based on these three considerations, the building is divided into five functional areas: 1) “foundations”; 2) “bearing structure”: all elements transferring forces; 3) “building envelope”: all elements dividing internal and external environment; 4) “finishings”: all elements that form and complete the internal building space structure (doors, dividing walls etc.); and 5) “services”: all electrical, heating, cooling, air-conditioning and communication services (as well as all additional special services arising from the specific building use).

These areas are assigned either to the "designed in project" or to the "pre-manufactured" branch or to both. In the following, the hierarchical structure within the branches as well as the reasoning behind it is outlined level by level.

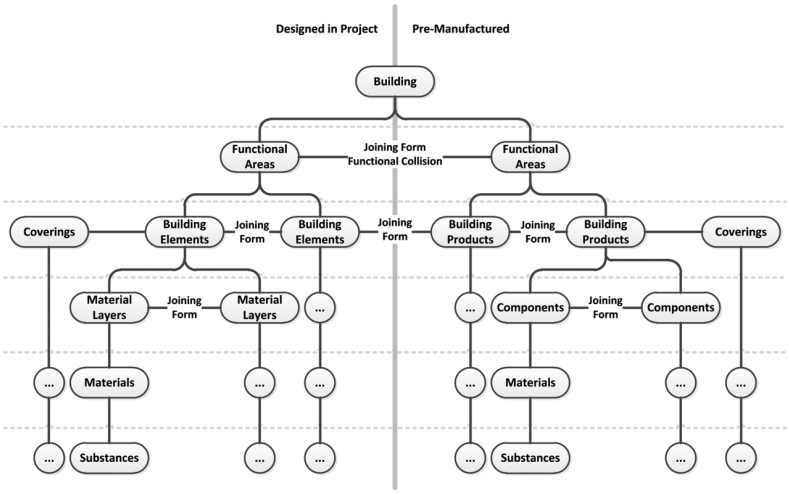

Figure 1. Proposed building model map.

3.1. THE "DESIGNED IN PROJECT" BRANCH

3.1.1. Substances

In this model, "substances" refer to material compounds on a chemical substance level that are not stand-alone materials of the building elements. There are two main arguments for the inclusion of substances in the model: human health and safety issues in the context of the comparably long life cycle of buildings and, secondly, material recyclability and reusability.

An important step towards substance management in building materials in the context of human health and safety issues was achieved with the introduction of the Material Safety Data Sheets (MSDS) with the regulation 91/155/EEC and the REACH regulation 1907/2006. Although they do not cover all substances (e.g. nano materials), they deal with substances and material compounds that could become hazardous or harmful in any phase of their life cycle. However, as material sciences belong to the most dynamic and progressive scientific areas, knowledge about materials and substances changes constantly. Thus, substances considered as harmless in greater amounts in the design phase of a building, could emerge as hazardous in small concentrations over time (e.g. asbestos, cadmium compounds).

Therefore, a suitable form for the exact localisation and complete documentation of substances in buildings beyond the requirements of the current MSDS regulation is necessary.

With regard to the returnability of materials in closed-loop material cycles in the built environment, there is a need for exact qualitative documentation of substances, too. Detailed knowledge about the exact compounds of a material is a crucial requirement for material recycling by means of well established technologies and methods as well as for the development of new, more efficient recycling technologies and approaches.

3.1.2. Materials

The term "materials" refers to the physical properties of a stand-alone material as well as additional analytical properties defined in this paper. These new properties stem from an analysis of the DfX-based material resource efficiency achievements in the automotive and electronics industries in the context of a fully integrated design process. They will be assigned to a design logic check and require a decision from the design team. Materials should be checked for recyclability in correlation with existing recycling technologies, allowing for recycling and reuse without downgrading (i.e. compound materials that can be recycled back to the same material compositions would be preferred).

3.1.3. Material layers and layer connection forms

Material layers inherit the complete material property set defined on the previous level and additionally contain the geometrical and location data parameters. The connection form between the single layers will be assigned to a design logic check, since inseparable layers result in a compound element, which, in general, can neither be reused nor recycled.

3.1.4. Building elements and joint forms

Building elements inherit the properties of their composing material layers and are assigned to groups. A check of the separability of the element joints will verify the exchangeability of the element throughout the life cycle in order to avoid conflicts with other elements resulting in material dissipation.

3.1.5. Functional areas and geometrical collisions

Building elements and element groups with the same function are assigned to a functional area. It is assumed, that the functional areas "foundations" and "bearing structure" are generally located in the "designed in project" branch while "finishings" and "services" are found primarily in the "pre-manufac-

tured" branch and the "building envelope" is assumed to intersect with both. Several different logic design checks will be performed on this level: the first is focused on the geometrical collisions between functional areas and should verify that – if available – the constructive solution still allows for the separability and exchangeability of elements. One example for a geometrical collision of functional areas is a cooling floor ("bearing structures" and "services"), which is represented on the element level by the embedding of cooling pipes in the concrete floor slab.

The next check addresses the overall design optimisation and focuses on the element groups in their respective functional areas, testing for minimisation/optimisation of the number of distinct elements in a given functional area and – subsequently – the material variety of said elements.

3.2. THE "PRE-MANUFACTURED" BRANCH

Generally, the objects contained in this branch should fulfil the same requirements and should be assigned to the same design logic checks as the elements from the "designed in project" branch. However, the data availability and quality as well as the form of documentation in this branch can strongly vary depending on the respective product and manufacturer. Hence, significant uncertainties could occur in the model within this branch and reduce the quality of the design check.

3.2.1. Substances, components and products

Crucial in this branch is the correlated impact of regulations and data standards used, since the designer cannot influence data quality and availability. Regulations guarantee the (manufacturer-delivered) data content and quality flowing into the model, while data standards ensure the transferability and automated usability of the data. With the evolution of the IFC data standard and BIM-based building design, some building product manufacturers have already begun to deliver the complete product documentation additionally as an IFC model or in compatible formats. These IFC product models can be directly embedded in the BIM and ensure a direct and complete exchange of metadata. The workflow and data exchange in such a case is the subject of a case-based research by Babic et al. (2010). In this context, an equal grade of data availability, detail and unified data standards on both sides ("designed in project" and "pre-manufactured") is a prime concern. Large deviations between the branches (e.g. very detailed "substance" data on the "designed in project" branch and no information on the "pre-manufactured" branch) would lead to unacceptable result uncertainties. In the regional legislation in some

countries (e.g. Denmark) IFC-format documentation is compulsory for publicly aided building projects, thus enabling the genesis of a resource data map for the built environment that can serve as a repository for future building resource management endeavours.

3.2.2. Functional areas

In the "worst" case of a design-bid-build organised building project, every single functional area is designed, ordered and built by a different sub-contractor and subsequently documented in a data format of his own choice. In this case, even given an active regulation demanding extended data availability and quality, the existing detailed data from the functional areas may be archived, but cannot actively be used after the completion of the building. Although the relevant data is available, it is downgraded to a waste product of the planning process by its lack of transferability and exchangeability (due to different data standards) and the sequential nature of the global design process. This gap is automatically bridged in the context of an actively implemented, IFC-based, fully integrated planning process.

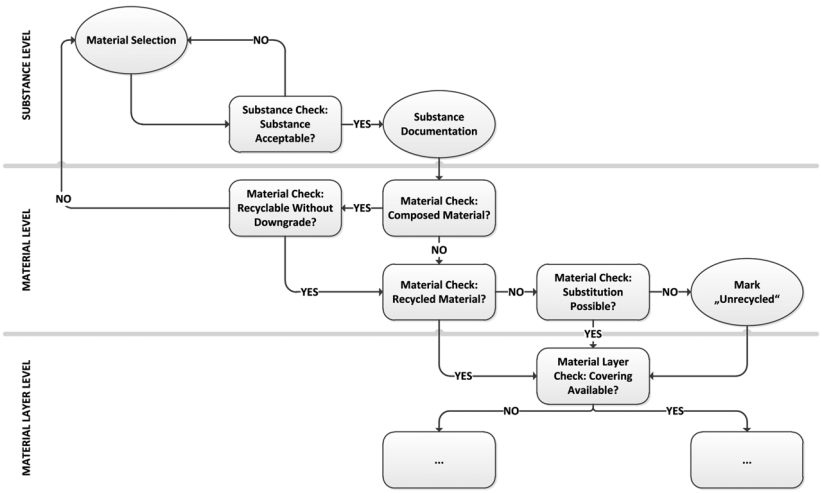

Figure 2. Excerpt of "designed in project" branch logic tree.

4. Logic-check trees

Based on the analytical building model map, logic flows for decision support can be identified. The logic trees are defined so as to offer a transparent and clear decision support for designers and give an instant feedback on the results of a decision.

The aim is to achieve a fully automated design check where designers can decide and understand the results of their decisions, but are not required to possess an extended and highly specific knowledge about processes and parameters pertaining to the material efficiency design check. In order to achieve this, a main requirement for future regulations is to verify that the substance and material data required will be delivered in adequate detail and quality and in the corresponding data format by the manufacturers.

In this paper, a section of the "designed in project" branch logic tree is presented that deals with the substance and material levels (see Figure 2).

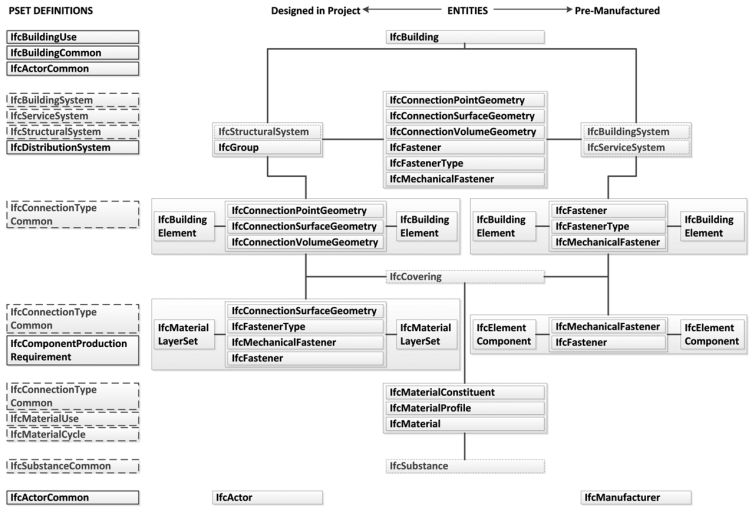

Figure 3. IFC-based data model diagram (extended or proposed are represented with dash lines).

5. The data building model

The translation of the analytical building model into IFC is based on IFC 2x4 RC3 (October 2011). The model primarily consists of IFC entities for the translation of the model elements and IFC property set definitions for the description of complex relationships which will be the subject of a design check. When required, additional IFC objects are proposed or the content of existing objects is extended (see Figure 3).

5.1. ENTITIES

Basically, IFC does not differentiate between "designed in project" and "pre-manufactured" building elements. The differentiation is therefore given by the

assignment to an IfcActor for the "design in project" or IfcManufacturer for the "pre-manufactured" building elements. To stress the difference, additionally an IfcStructuralSystem is proposed. An additional IfcServiceSystem defines explicitly the "services" functional group. The existing IfcBuildingSystem is assigned to general and special functional areas that are heterogenous (i.e. can be assigned both to "designed in project" and "pre-manufactured") such as "finishings" or to special functional areas arising from the specific building use.

Another additional IFC entity proposed is IfcSubstance. It corresponds to the "Substance" function and definition in the analytical model and is subordinate to IfcMaterial and IfcCovering in the data model.
The material usage in the building is defined on the material level by IfcMaterial as well as IfcMaterialProfile and IfcMaterialConstituentSet for the identification of composite materials.

5.2. PROPERTY SET DEFINITIONS

For the purposes of an IFC-based design check (which is the subject of a later phase of the project and not presented in this paper), new IFC property set definitions are defined. Exemplarily, the property set definitions for substances and materials are demonstrated in the tables below.

TABLE 1. PropertySet Name: Pset_SubstanceCommon.

Name	Data Type	Definition
Reference	IfcIdentifier	ReferenceID for the specific type in the project
Listed	IfcBoolean	Indicates whether the substance is marked as listed according to current safety classifications
Composition Rating	IfcBoolean	Indicates if the substance is identified as an "impurity" with regard to the containing material and will therefore cause a downgrade in the recycling process

TABLE 2. PropertySet Name: Pset_MaterialCycle.

Name	Data Type	Definition
Reference	IfcIdentifier	ReferenceID for the specific type in the project
Composite	IfcBoolean	Identifies if the material is a composed material (according to manufacturer data sheets)
Recycled	IfcBoolean	Identifies if the material is a recycled material
Recyclable	IfcBoolean	Identifies if the material is recyclable

6. Conclusions and further work

In the context of a fully integrative design process, available software interfaces and unified data standards, the information transfer and storage can be organised automatically into a building model and thus, be used, adapted and completed over the life cycle of a building. The design check logic flow based on the models presented in this paper will be applied on a case study performed completely in a BIM to identify further implication deficits. For the optimised data model and design check logic flow, an IFC rule-based checking algorithm according to the methodology of Eastman et al. (2009) will be defined and tested on building projects in practice.

As a future challenge, the management of intellectual property, patents and corporate manufacturing secrets for building products will have to be addressed. The hypothesis assumed is that the qualitative documentation of the substances in pre-defined percent ranges is the deciding factor and not the exact quantitative description – this should effectively ensure a balance between industry and owners' interests.

Nevertheless, the history of Design for X adoption in the automotive and electronics industries shows that without the corresponding regulations, the environmental and social incentives most likely will not be enough to initiate the changes necessary.

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LOCALISED DESIGN-MANUFACTURE FOR DEVELOPING COUNTRIES

A methodology for creating culturally sustainable architecture using CAD/CAM

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Abstract. This paper demonstrates the production of endogenous solutions for global development when applying local workforce skills in the design-manufacturing process using available computer-aided design and computer-aided manufacturing (CAD/CAM) tools. The methodology outlined in this paper improves technology uptake in developing countries by promoting localisation of the design-manufacture process coupled with local knowledge to promote culturally sustainable technology dissemination. This paper documents a set of design rules and manufacturing methods used to create precision moulds with locally available CAD/CAM tools. The moulds shown here were used by local craftsmen in the casting and construction of a prototypical precast architectural system deployed in the urban slums around Nairobi, Kenya.

Keywords. CAD/CAM; CNC; cultural sustainability; assembly systems; global manufacturing.

1. Introduction

African urban populations are expected to triple over the next 30 years. Around 2030, Africa's collective population will become 50 percent urban, leading to an exponential increase in the demand for shelter and services. Globally, urbanisation is associated with more job opportunities and improved human development; however, th is is the reverse of the socio-economic conditions currently prevailing in African cities. Demographic expansion is continuing regardless of ever-growing shortfalls in housing, services and livelihood

opportunities (UN-Habitat 2010). It is clear that the challenges of African urbanisation will not be met through the current architectural design and construction industry. Already, basic services are not accessible to many African urban residents. What is needed are new ways to promote multiple benefits through novel methodological solutions. These solutions are needed for humane development that can be scaled and widely implemented. In Kenya, and across Sub-Saharan Africa, CAD/CAM equipment has the ability to significantly enhance technology dissemination globally and further promote the practice of architecture in developing countries. Enabled by the global distribution of Gershenfeld's (2005) Fabrication Laboratories (FabLabs) and connectivity provided by the digital age (Resnick 2002), the process of development and building infrastructure can significantly move forward with the use of appropriate CAD/CAM technologies coupled with sustainable methodologies. This paper presents an initiative that intends to demonstrate the value of these technologies within a specific context.

2. Context

In Kenya, and in developing countries worldwide, the urban informal settlements (slums) not only require solutions for adequate housing, but also basic service infrastructure including water, electrical, and sewage systems. The lack of sanitation infrastructure is a crisis of incredible magnitude. Over 2.6 billion people – 40 percent of the world's population – lack access to adequate sanitation. The problem is particularly acute in slums, where high population density combined with the lack of sewage infrastructure and resources result in no access to sanitation for 80 percent of slum dwellers. Most residents living and working within these informal settlements are employed within the informal craft sector. This sector is made up primarily of the Jau Kali who are entrepreneurs and craftsmen with trained skills representing a wide spectrum of local production practices. The Jau Kali way of working can be described as bricolage, in which necessity and recycled materials become the cornerstone of each creation. Their way of working is iterative, reworking until the product performs its intended task; resulting in minimal product waste. The Jau Kali are creative and ingenious inventors, although limited by their materials; thus, the quality of their production can be unpredictable. As Kenya aims to position itself within the global economy, many living and working within the informal economy fear marginalisation with the introduction of new technologies. For advocates of sustainable development in regions like Kenya the question remains, "Why use highly technical exogenous machinery when there is an abundance of local labour?" This paper describes the benefits and synergies that arise when new, appropriate technology is adopted by local

craftsmen within a network of distributed industries in an approach described here as Localised Design-Manufacture.

3. Innovation

The methodology of Localised Design-Manufacture is based on the principle that within the development context production processes must consider the local abundance of skilled technicians and assemblers. Unlike traditional manufacturing which aims to streamline the production process, this methodology promotes building local capacity by incorporating a feedback loop that links a local engineer to a local assembler, or craftsman, throughout the design and production processes. In this way the local craftsmen can be involved in the development of their own community, as the consumers and producers.

Localised Design-Manufacture promotes working within the community, recognising the skill of the local informal workers while augmenting that capacity through the introduction of new, global technologies. The precision and efficiencies provided by highly technical machinery can bring noticeable material cost savings while maintaining safety measures in the construction of architectural and infrastructural assemblies.

3.1. ECO-SAN SOLUTION

In the summer of 2010, a team of engineers and designers from the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, USA partnered with an engineer and technician from the Science and Technology Park at the University of Nairobi (Nairobi-FabLab) to manufacture a low-cost sanitation centre using digital design and fabrication tools available at the University of Nairobi. The principals of Localised Design-Manufacture were utilised throughout the process of CAD/CAM fabrication to surface sculpt a precision mould plug for a fibreglass mould used to pre-cast ferrocement components. The team addressed the lack of sanitation in slums with a low-cost solution that could be pre-manufactured and easily assembled on-site, employing local labour throughout the design and manufacturing processes from skilled fabrication technicians to on-site assemblers. The development of the Eco-San toilet for the informal settlements of Nairobi can be seen in Figure 1. As a result of utilising the Localised Design-Manufacture methodology in the development of the Eco-San solution the assembly achieves technical performance and community adoption while enhancing skill sets and digital expertise. Features of the assembly include:

Pre-Fabricated, Pre-Cast Materials A precast ferrocement assembly with integrated tongue and groove connections allow for rapid production

and assembly of quality components, while reducing cost and use of materials. At $200 USD to cast each unit, the cost is comparable to the more commonly used pit latrines with bush pole and corrugated metal substructure.

Figure 1. Application and production process used to solve a real-world sanitation problem utilising local resources and labour (2010).

Durability Ferrocement is both highly durable and low maintenance. The pre-cast, monolithic floor plate provides a register for the superstructure, by locking in the walls and corners in combination with the monolithic, precast roof ring. The panels are structurally engineered for the demoulding and transportation of the pre-cast parts.

Assembly and Flexibility Due to its compact, modular size the assembly can be implemented on site at the block level where it is needed most. In order to eliminate an on-site staging area and formwork, foundation posts are pre-cast which allow for levelling the floor plate during the assembly process. In this way, the assembly can be placed on sites undesired for other types of construction.

Designed for Lack of Sewer Infrastructure The waste is easily accessed from within the unit by lifting the light-weight, rotationally moulded, plastic squat plate on a daily basis. This no-flush design is important in slums where there is minimal existing water and no sewer infrastructure.

Cleanliness Precision moulds allow for the design to incorporate complex curves like filleted corners along the low-wall of the floor plate and in the L-shaped corner panels. This adds to the durability of each component while eliminating crevices that normally collect dirt, increasing the perceived cleanliness of the toilet assembly. Water-reducing measures are particularly important for communities within Sub-Saharan Africa where the cost of water, a commodity used in cooking and cleaning and drinking, is often more expensive than a fruit juice or soda.

4. Localised Design-Manufacture Eco-San Process

Employing the Localised Design-Manufacture methodology to create the Eco-San solution the team relied heavily on a series of field tests and processes for arriving at the best mix of innovative and appropriate technologies for the project. These tests outlined below produced an accurate and replicable design solution to the real-world problem of sanitation within the informal settlements around Nairobi, Kenya.

4.1. LOCALISED DESIGN PROCESS

When working within developing countries, meeting the formal necessity is not a catch-all solution; for maximum impact and uptake, one must consider the cultural implications of the process in which it is achieved. The novelty of the Localised Design-Manufacture methodology is that it necessitates a design process that incorporates craft and *democratises* the CAD/CAM process, while maintaining cultural sensitivity. Achieving these goals is what transforms the methodological proposal into a design exercise in which design sensibility is deployed to achieve cultural sensitivity. It is the combination of appropriate technology and local context that can facilitate development in a culturally sustainable manner.

4.2. LOCALISED MANUFACTURING PROCESS

In Nairobi, a hub of East Africa's industrial production, there are few highly technical machines and manufacturing processes aside from large and established industries such as the Nairobi Railway. However, in 2009 the Science and Technology Park at the University of Nairobi built a FabLab that houses a set of prototyping equipment that is accessible to budding entrepreneurs. Projects which have been successfully incubated within the FabLab include a flexible biogas digester, a vehicle tracking system, a set-top box to convert analogue TV to digital, and a wireless mesh network system called Fabfi.

CAD/CAM processes are well positioned for widespread adoption by providing benefits to the craftsman, including repeatability, precision, replicability and scalability, without compromising customisation. "Real" mass customisation, as defined by Schodek et al. (2005), is a manufacturing process which creates varied architectural components, not restricted by industrial repetition. Though digital tools may require more time to produce a first working prototype compared to traditional hand-crafted methods, long-term productivity is dramatically enhanced due to ease of iterative design improvements and repeatability. Within the Eco-san development the Jau Kali on the team became convinced of the benefits of investing in these new processes as productivity and profitability potential were improved through the pre-cast, precision mould manufacturing process.

4.2.1. Benefits of pre-cast ferrocement

As stated above, when approaching localised manufacturing the process must first consider available local resources and local production methods that can benefit from digital production. Within Nairobi ferrocement construction is one such process that can benefit from digital fabrication, commonly used

for water storage tanks and other monolithic forms, traditionally cast in-situ. The technique is well established with the Jau Kali who construct these thin-shell concrete structures reinforced with hexagonal chicken wire mesh. The Eco-San design team used ferrocement in a pre-cast system to control the quality of the assembly with a digitally fabricated, precision mould.

Pre-cast precision moulds are used similarly to the local technique of sand casting, another process that can benefit from the precision of digital production. Where the precision mould is milled from solid material, a sand cast is a reductive process of removing or packing ground material until a negative can be formed in which a craftsperson can cast their monolithic form. In sand casting, the first cast form is used in subsequent casts as a plug to create future moulds in the sand. In each process the quality of and reusability of the plug saves on time and cost. The pre-cast process used in the Eco-San solution utilised the Jau Kali's transferable processes and skills. The pre-cast precision mould, however, provided many benefits in cost savings, quality control, as well as easy, on-site assembly and maintenance, while employing local labour.

4.3. DIGITAL FABRICATION

The Eco-San solution was designed to front load the effort of skilled technicians during the digital design and fabrication of the precision molds to limit the amount of skilled labour required on-site, thus reducing the final cost and increasing access of the final assembly to the community.

The manufacturing process used in making the Eco-San floor plate used the process of CAD/CAM fabrication employing computer numerical control (CNC) technologies to surface sculpt a precision mould-plug for a fibreglass mould used in pre-manufacturing highly accurate ferrocement components. Utilising computer-generated designs and digital fabrication within the FabLab the design team partnered with a local technician and engineer to iterate the design of the precast sanitation unit rapidly and replicate positive results. The Figures 2–5 below illustrate the fabrication process of the floor plate mould from digital model through mould fabrication.

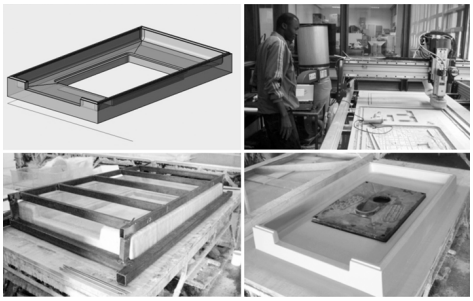

Figure 2–5 . Floor mould design as digital 3D model. Milling positive plug from composite board in Nairobi FabLab. Fibreglass mould and steel frame made from plug. Final fabricated floor plate plug.

For non-industrial manufacturing of infrastructural components,

as promoted in the Localised Design-Manufacture process, the design team had to create high precision moulds without the need of energy consuming equipment for injection blowing, vibration, and compression. This can was achieved by creating a single-sided, open-face mould, leaving just one plane of the cast volume to be trowel finished.

Creating a single-sided mould has many benefits. Technical benefits include the relative simplicity of the fabrication equipment required to mill the plug, it is predictable and can be achieved on most 2.5D CNC routers, as found in the local FabLab. Additionally, it reduces the amount of material to create the mould, a goal for any production process when working within a material-restricted area, as is Nairobi. In general, moulds are more affordable and consume less energy to transport than casts, promoting localised and distributed manufacturing. The design team began the mould fabrication process with a virtually modelled component representing the final cast form. The digital model was used to test in virtual space, before production, that the proper tolerances were built into the precision mould and that the resultant cast components would fit together in the final assembly. The technical challenge came in designing the form for a single-sided mould. The design had to make sure all precision elements, including the framing edge and joints, were cast within the finished mould for higher accuracy in the assembly. Undercuts, as found in the integrated joinery elements, were avoided by locating all joint connects onto one surface of the mould – the bottom.

Capacity building Throughout the digital design and manufacturing processes there were opportunities for building local capacity, a necessary step in the Localised Design-Manufacture process to ensure the eventual community uptake and full integration of new technologies. During the summer of 2011, in partnership with the Nairobi-FabLab, the design team hosted a digital modelling and fabrication workshop for a multi-disciplinary group of university students. Participants learned basic digital modelling skills through a lesson demonstrating the process of exporting a digital model to the digital fabrication tools found within the local FabLab. Each student was then assigned the task of modelling a design related to their own research, proceeding from conception to realisation. Many of the students have since contributed to the development of the Eco-San solution and continued investigations utilising their digital fabrication skills.

4.4. MATERIAL DEVELOPMENT

Localised Design-Manufacture contributes to the identification of sustainable construction methods and the consideration of innovative materials and assembly systems (Fernandez 2006). During the Eco-San development, inde-

pendent material research was conducted within the Concrete Materials Lab within MIT's Department of Architecture with the goal of material efficiency for cost-reduction. The team worked to develop and test a concrete mixture and configuration that would be efficient, yet structurally sound, using all locally sourced materials. The investigations included cost-reducing concrete mixtures found in Kenya; including plastic pellets, a recycled industrial by-product, for aggregate, while others incorporated admixtures like volcanic ash and fibre reinforcement.

Structural testing During the month of January 2011 the design team led a casting demonstration for students and local craftsman with the University of Nairobi's Civil Engineering Department. The casting demonstration included a series of ferrocement wall panels with the goal of performing structural tests showing the effectiveness of each cast, shown in Figures 6 and 7. The tests included the control sample which replicated the mixture used in the Eco-San solution built in the summer of 2010, chicken wire reinforcement within a 1.5 inch thin concrete slab; as well as two variations on the control sample, one used layers of distributed mosquito netting as a substitute for chicken wire and another used recycled plastic pellets to replace the quarry dust aggregate. The variables compared in each cast included; self-weight, tensile and compressive strength limits, as well as the catastrophic failure point, and associated cost of each mixture. It was found that four layers of distributed mosquito netting roughly .25 inches apart saved time in casting and reduced cost compared to the chicken wire reinforcement which required a welded steel frame to lay flat in the composite. Structurally, the chicken wire with rebar could carry a larger load before catastrophic failure. However, the chicken wire cast showed early deformation compared to the mosquito netting which failed suddenly at a higher weight.

Figure 6 and 7. Three-point bending test of panels for use in pre-cast assemblies. Sec tion of panel with mosquito netting after catastrophic failure.

4.5. ECO-SAN RESULTS

The efforts of design to manufacturing detailed above culminated in the form of a sanitation solution that is environmentally, culturally, and financially sustain-

able and provides hygienic sanitation to those living within the informal settlements around Nairobi. Additionally, local capacity building was achieved for the engineers and craftsmen that were employed throughout the process. To further understand the potential of this system the local team has continued to scale-up the production and assembly efforts to span new geographic locations.

5. Improved community uptake

While the digital modelling and manufacturing technologies used in the Eco-San solution are not new, researchers, engineers and designers have only recently introduced the use of CAD/CAM in developing regions. The Instant house (Botha and Sass 2006) utilises CAD/CAM to fabricate plywood components into a bi-lateral assembly. The investigation of an interlocking concrete block assembly by Griffith uses CAD/CAM to manufacture a cradle moulding device appropriate for local adoption in rural applications (Griffith et al. 2012). Each of these techniques proposes a feasible methodology for creating designs in a virtual environment to physical output for production in the local context. However, following their trajectory of digital manufacturing tools in the global context would suggest that "all decisions have to be taken before production starts…" and that the craftsman cannot use his/her experience, becoming merely an assembler of pre-manufactured parts because the assembly sequence is already determined by the designer (Papanikolaou 2008). As a result, there is limited capacity growth within the local craftsmen to maintain the production methodology without exogenous assistance.

Thus, during the development of the Eco-San solution the team addressed the problem of inadequate sanitation in Nairobi's slums using the Localised Design-Manufacture methodology in the design of precision moulds to manufacture and deploy low-cost, water-free toilets. The local team is currently developing ongoing design iterations of the precision moulding system for other infrastructure applications along with developing localised distribution channels for the Eco-San design to be replicated and scaled to meet sanitation needs across sub-Saharan Africa. A new construction industry is being formed around the methodology of Localised Design-Manufacture generated by local need and local labour.

5.1. BROADER APPLICATIONS

Scalability is the most critical element to increased technology uptake. As the Localised Design-Manufacture process and products are replicated and scaled across nations, skill levels, and functions they will prove to be independent of their creator. It is this autonomy, or transfer of accountability, which represents

a complete technology adoption, no longer reliant on exogenous resources. In the developing world context, scalability also offers the prospect for the creation of new modes of employment and enhanced skills not otherwise possible. Once a methodology is found applicable for wide-spread adoption, combining craftsmanship with CAD/CAM tools, the broader design, engineering and economic implications of this synthesis can be further explored. Additionally, once the tools and design documentation are standardised globally, the co-creation and bi-directional exchange of new developments can be shared and open-sourced through sustained channels of communication among diverse academic and industrial communities.

6. Contribution

The prototype using the Localised Design-Manufacture methodology offers a framework for localised design and manufacturing of other architectural and infrastructure solutions requiring precision manufacturing within developing countries. Further research has been committed by the local technicians for the development of housing modules, bio-gas digesters, food storage, and networked sanitation systems. As a substantive productive process, concerned with craft and assistive digital technologies for global development operating at a local level, the Localised Design-Manufacture methodology is evaluated quantitatively on performance and local socio-economic criteria, as a qualification for cultural sustainability. As this paper demonstrates, when designing within developing countries it is important that designers exercise flexibility in rethinking the entire production process and acknowledge the coupling of technology and local context.

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ROBOTIC RETICULATIONS

A method for the integration of multi-axis fabrication processes with algorithmic form-finding techniques

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Abstract. This paper addresses the design and fabrication of non-uniform structural shell systems. Structural shells, particularly gridshells, have a long history but due to their complexity and the accompanying high cost of construction, their application has been limited. The research proposes a method for integrating the design and fabrication processes such that complex double curved reticulated frames can be constructed efficiently, from prefabricated components, requiring significantly less formwork than is typical. A significant aspect of the method has been the development of software tools that allow for both algorithmic form-finding and the direct control of robotic fabrication equipment from within the same modelling package. A recent case-study is examined where the methodology has been applied to construct a reticulated shell structure in the form of a partial vault. Components were pre-fabricated using 6-axis robotic fabrication equipment. Individual parts are designed such that the assembly of components guides the form of the vault, requiring no centring to create the desired shape. Algorithmically generated machine instructions controlled a sequence of three tool changes for each part, using a single modular fixture, greatly increasing accuracy. The complete integration of computational design techniques and fabrication methodologies now enables the economical deployment of non-uniform structurally optimised reticulated frames.

Keywords. Reticulated frame; robotic fabrication; dynamic relaxation; form-finding; computational design.

1. Introduction/background

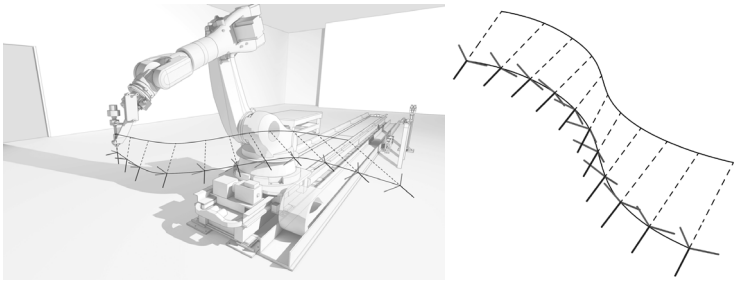
Building design is becoming increasingly complex; structural, environmental, and programmatic requirements are necessarily intertwined with tectonic and formal design decisions. The ability to discretise multiple performance requirements has prompted the adoption of algorithmic approaches to design, allowing the precise and explicit negotiation of complex design parameters. Typically, algorithmic design strategies produce an output that is parametrically varied, and often generate components unique in size and shape. While at first the digital design and fabrication workflow may appear to create vast reductions in the labour of the design process, very often it simply shifts the labour from one aspect of design to another (Scheurer 2008). Significant work remains to be done to streamline the process from design conception to design realisation.

This research has been conducted as part of a larger body of work, which addresses the increasing complexity of the design and fabrication workflow (Pigram and McGee 2010). The research proposes that as opposed to a top down/serial approach, that the production process must be understood as a feedback between design and a multitude of constraints related to fabrication, materiality, and tectonic strategies. Of central importance to maintaining this feedback loop is the development of software that allows the designer to seamlessly migrate between design and fabrication, minimising one-way translations and the "reworking" that frequently occurs when fabrication constraints are not adequately understood during the conceptual design phase.

Specifically, this research has made use of fabrication scripts developed within a native CAD program. In this case, Rhinoceros 3d and RhinoScript have been used as a test bed for these custom software tools. The design and production of the prototype makes use of custom scripts which have been developed over a period of two years. Several groups of researchers have developed similar methodologies using Rhino and Grasshopper and other packages (Brell-Cokcan and Braumann 2010). What is important is not the particular program or scripting language, but the development of more numerous and more robust feedback channels between designing and making.

An advantage to this workflow rests on having algorithmically generated geometry. This allows fabrication output can be seamlessly integrated into the code framework, allowing a direct connection between the actual machine instructions and the underlying geometry of the design. Integrated simulation

and inverse kinematic verification (Figures 1 and 2) give the designer near instant feedback to fabrication issues such as reachability and collisions. The software tools were developed with open source distribution in mind. Currently it has been ported to multiple robot control languages, as well as to CNC G-code and Cartesian/hybrid kinematic systems.



Figures 1, 2. Robotic simulation; Toolpath vectors.

As a specific application of this integrated workflow, the design and construction of a prototype structural shell system has been conducted. Several types of structural shell typologies exist, including grid shells and reticulated surface shells. Grid shells are structural systems that make use of a regular grid of structural members that are continuous and fixed only at ends (Figure 3). The members are assembled into a lattice that has a quadrilateral grid topology. This lattice is then deformed into the required curvature for the design, before being pinned at the intersections of the lattice. Shell structures are often characterised by large open spans, and double curvature in the overall form, which provides the shell with its structural performance, allowing the overall shell to be surprisingly thin.

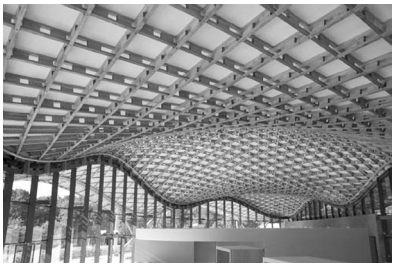


Figure 3. Savill Garden Visitor's Centre, Glenn Howells Architects 2006.

Often grid shells are confused with reticulated surface shells, which typically use approximately equilateral triangles as the base grid. These shells cannot be "flattened" physically during construction. The system investigated here is

a type of reticulated surface shell, as the inability to be "flattened" is an important aspect of the approach.

The difficulties of this approach are immediately obvious from a fabrication standpoint. Irregular components require advanced fabrication methodologies. In the case of the grid shell, the system requires deformation or assembly onto precise scaffolding or centring systems, in order to achieve the final, designed form. In reality the optimal solution is often a hybrid of the two approaches.

2. Approach

This research has combined three aspects of enquiry into a coherent methodology: algorithmic form-finding; detailed tectonic and assembly development; and parametrically driven multi-axis robotic fabrication. In order to develop a structural system that maximises material efficiency, custom written dynamic relaxation software was used to "form-find" the resulting double curved shell geometry (Figure 4). While relaxation itself is far from novel, this implementation (written in Java) incorporated a series of valuable additions tailored to its specific use as a vault design tool. These additions were primarily interface related, designed to allow for, and to take advantage of, real-time adjustments to parameters during the form-finding process.

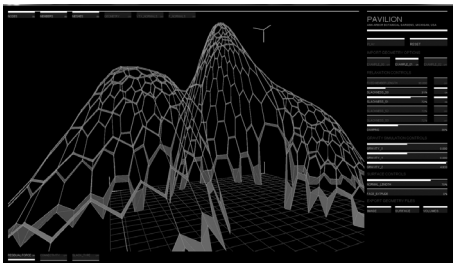
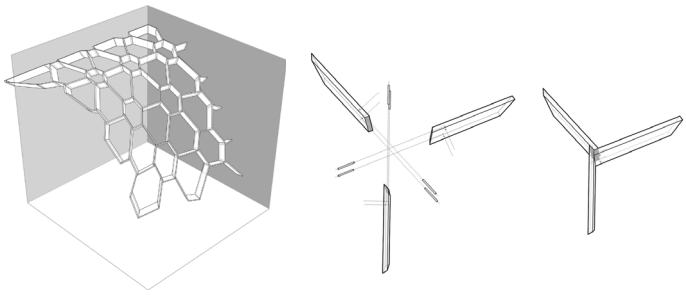


Figure 4. Custom dynamic relaxation software, written in Java.

Initial member geometry (of arbitrary topology) can be separated into a series of layers/groups, so that during the relaxation each group of members could have its own slack-length varied via a series of sliders. This functionality allowed for the development of a sophisticated intuition as to the emergent behaviour of the system. It also allowed for a nuanced control of the overall form while maintaining structural integrity. This affordance is not usually present in dynamic relaxation processes, which can tend to be overly initial-state dependent. In the reticulated surface described in this case study (Figure 5), differentiated slack-lengths were used to navigate a very tight situation while ensuring individual joint angles and member lengths remained within

fabrication limits (such as the requirement to overhang the edges of vacuum fixturing supports).

The design, development and testing of the specific joint tectonics of the system formed a significant segment of the enquiry. In order to produce a flexible structural system, which could react to the various potential inputs (many of which are not considered at this point), the relaxation software was developed to allow the user to specify the base grid topology. The initial prototype has been developed using a grid of hexagonal topology. This grid allows for a specific range of joint angles to be established at the nodes, which are always intersections of 3 members (Figure 6). This is significant because highly oblique angles generate cutting operations that engage large amounts of material and are therefore problematic.



Figures 5, 6. Reticulated frame prototype; three member joint.

A central benefit of this methodology is that the overall form of the grid shell is embedded into the form of the prefabricated components, which are self-aligning during assembly. The use of complex centring and or scaffolding (Figure 7) to create complex grid shell structures is well documented (Paoli 2007), however, the material and fabrication costs associated with such methods make them prohibitively expensive.

Figure 7. Height adjustable scaffolding on Alvaro Siza's Serpentine Pavilion.

Due to the potential for compounding errors, the proposed method requires very tight tolerances during component fabrication. With multi-axis machining, the tolerances of the machine can be difficult to quantify. In the specific case of 6+ axis robotic systems, the overall accuracy is inconsistent across the work envelope of the machine (this problem also exists for large CNC machines), and can at best be calibrated to within 0.5 – 1 mm spherical error. This must be considered at the design stage as is has considerable effect when considered in concert with the requirement for 'self-alignment.'

The fabrication process relies on several features to realise a large number of unique parts efficiently. While all of the parts are geometrically unique, they are topologically similar (with the exception of boundary conditions), possessing 4 sides, a consistent number, sequence and arrangement of holes, connections and processes (routing, sawing and drilling). Members are pre-cut from flat stock using a 3 axis CNC router. They are initially approximated by a bounding box for nesting (Figure 8) to enable placement on the riser pods used in subsequent machining. More complex machine configurations exist that can accomplish this process in one setup.

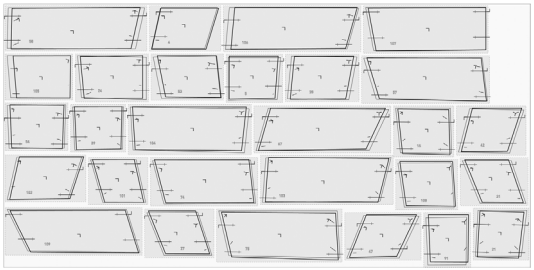


Figure 8. Nested cut sheet.

An effort was made to minimise the visibility of hardware at the nodes, while maximising structural integrity of the joint. A bolt pattern that allowed the six bolts required at each node to "pass" each other was selected while acknowledging the inherent compromise of each pairs location relative to the structural optimum. The combination of the compound miters and the placement of holes in each piece generates the desired curvature across all nodes.

As a result of the structures double curvature each node has a unique normal vector. To avoid this property translating into the requirement for twisting member forms all member centerlines are extruded towards a single point. This is crucial to allow the members to be cut from flat sheet stock while avoiding residual stresses within the overall structure. It is still necessary that the thin inner and outer surfaces of each member be ruled surfaces; this avoids any stepping at the top of the joints that would have resulted from the material

thickness if 3 axis cutting techniques were employed. Traversing from a node to its adjacent node along a single member, the surface 'sweeps' so that each end is perpendicular to its nodes normal.

The precise alignment of the hole system and the compound mitre that drives the overall curvature across nodes. In order to learn from a worst-case test of the fabrication strategy, the holes for the case study connections are designed with zero tolerance.

2.1. FABRICATION PROCESS

Each piece was placed on the riser pod, and then underwent three operations via a robotic milling workcell. Tool changes were performed automatically, and each part took around 2 minutes to fabricate. The first operation (Figure 9) made small slots to accept a square threaded fastener.

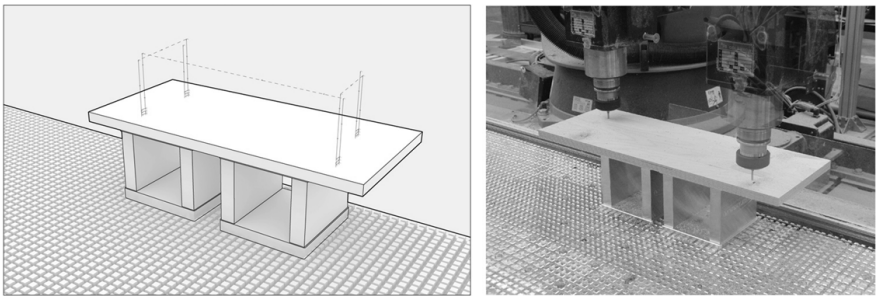
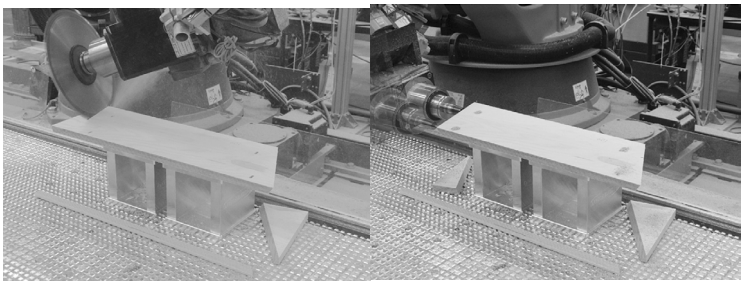


Figure 9. Slotting operation.

The second operation utilised a 300 mm saw blade fitted into a spindle (figure 10). The saw was chosen due to the high feed speeds achievable, with lower forces on the part as compared with a router. Low reaction forces are an important requirement, as the small surface area of parts makes vacuum-fixturing difficult. Surprisingly, it was possible to perform the variably swept edge cuts using the saw; intuition would suggest that a saw must be run straight in material. As described above only the longer edges twist, the end cuts are straight intersections.

The thickness of the part has a large effect, and the maximum rate of twist per unit length was determined experimentally. Exceeding this rate of twist resulted in friction and burning on the face of the blade or in lifting the piece of the vacuum pods.

The final operation utilised a drill in order to create the end and face alignment holes (Figure 11).



Figures 10, 11. Saw cutting operation; end-hole drilling operation.

The accuracy of these holes became an area of intense study, as initial tests yielded parts that did not assemble correctly. Ultimately, due to the inaccuracies present in large robot kinematics, a solution was found that used tool calibrations that were local to each of the orthogonal work planes involved. The geometric similarity of the parts was important for this to be successful. In general, fabricating parts with these tolerances would be better suited to 5 axis routers, which have accuracies 10–50 times better than equivalently sized robots, and the high rigidity needed to cut harder materials.

The initial material fabrication studies have been performed using 18 mm Baltic birch plywood. Four sheets of material were used to produce the prototype. This material provides approximately isotropic properties parallel to the lamination plane, and the $4' \times 8'$ form factor allows for nesting to utilise material efficiently. Further testing utilising glue-laminated beams with the lamination plane perpendicular to the local surface normal of the node (currently the lamination plane is parallel) is planned for comparison.

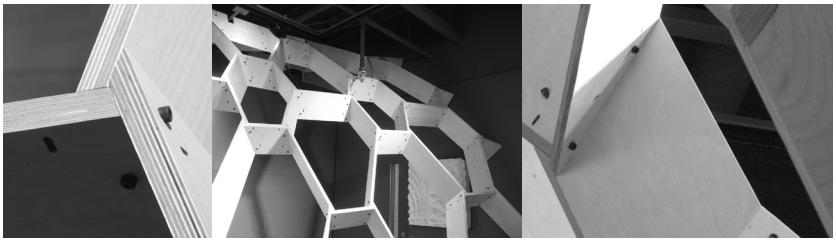
3. Findings

The initial assembly of the grid shell prototype yielded several insights into the methodology. Overall accuracy of the prefabricated parts varied. Certain nodes were very accurately aligned (Figure 12), while others were off by approximately 2 mm between adjacent members along the normal vector of the node.

Over large spans, variation in the actual length of members would be significant, and would require allowance to be made at the boundaries of the grid shell. The variations in node alignment that were observed are most likely due to the aforementioned machine accuracy issues. Subsequent calibration of the robotic workcell via FARO Laser Tracker indicated the overall volumetric accuracy with a mean error of 0.5 mm and a max error of 0.8 mm. This is only valid for the checked positions in the calibration. Intuitively the drilling

operation represents a worst-case situation for the robot, where the drill axis traverses across 180 degrees of orientation, and the kinematic pose is significantly different between the two ends of each member.

Accuracy issues notwithstanding, the components were within the tolerance required for assembly, even with zero hole/fastener tolerance (Figures 13 and 14). Wood tends to be forgiving in this respect, as misalignment simply results in local material failure. The tectonic design ensures any of failures of this sort are concealed within the joint. Further research is needed to quantitatively test the joint tectonic employed. Predicted failure modes would be shear failure resulting in bolt pull through, and/or splitting failure between the plys of the lamination. This is significant as the bolt-holes act as stress risers for this mode of failure.



Figures 12, 13, 14. Node detail; Completed reticulated frame prototype.

Figure 15. Alignment of Alvaro Siza's Serpentine Pavilion with Optical Metrology.

As an initial prototype, the structure behaved as expected, requiring no additional support during assembly. For larger spans the potential for component misalignment would compound and compounding errors could result in the load path deviating from the structurally relaxed form. As such a realistic method for the fabrication of large complex grid shells will require a hybrid

of prefabrication and onsite assembly control. While accuracy in the prefabrication of members is imperative, assembly tolerances will always exist. The research leads to new questions of how onsite construction practices, traditionally slow to change, can be augmented with technologies which allow compensations and corrections to be implemented to increase the overall efficiency of the system. One important area of study is the integration of onsite metrology methods in the assembly process, as current techniques are typically time consuming and labour intensive (Figure 15).

4. Conclusions

The complete integration of computational design techniques and fabrication planning methodologies opens up the possibility of economical deployment of non-uniform structurally optimised grid shells, while providing the opportunity for external design inputs, site-specificity and material efficiency to be incorporated algorithmically. Significantly the prototype and this research contribute to the larger ambition of tightly integrated feedback loops between design conception and design realisation achieved through computation.

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JUNK

Design build studio

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Abstract. The paper presents a design build studio that investigates the role of waste as building material and develops a proposal for an installation that uses CAAD and CAM tools in combination with traditional fabrication tools to design and build an installation out of waste materials. The paper describes the concept development and the construction process through the help of computational tools. Recycling is in the process of becoming an integral part of sustainable architecture. However, there are very few digital design projects that use re-used or recycled materials in combination with their architectural and aesthetic qualities and potentials. The potential of such an investigation is explored within a design build studio. What is junk? What is a building material? What are the aesthetics of junk?

Keywords. Education in CAAD; digital fabrication and construction; practice-based and interdisciplinary CAAD; parametric modelling.

1. Introduction

In January of 2011 the ETH Zürich introduced a student competition for the Global Alliance of Technological Universities. The participating universities included ETH Zürich of Switzerland, the Indian Institute of Technology of Bombay, India, Shanghai Jiao Tong University of China, Nanyang Technological University of Singapore, and the Georgia Institute of Technology of Atlanta, USA. The competition sought to enhance complex holistic thinking in a sustainable context through a challenge to participating schools: Build a tower using only local materials, your know-how, and your hands that is a symbol of your country, region, or university.

The idea of the competition organisers was to investigate aspects of sustainability in a collaborative design built project. Each team consisted of 8–12 students with a given budget of $1000 and a time frame of three months to complete and document the competition that included four phases: conceptual development, design, material collection, and construction. The teams were restricted to using local materials and to constructing their entries in a single week.

2. Studio approach

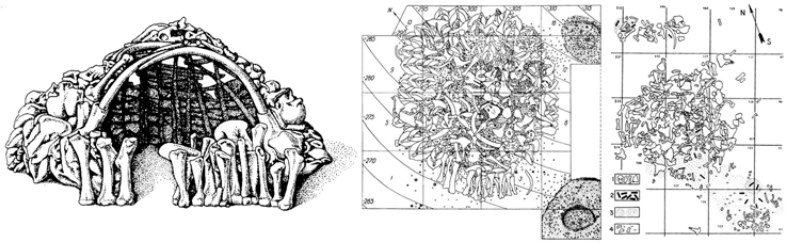

Figure 1. The mammoth bone huts of 16,000–10,000 BC are the earliest known example of reuse, Mezhirich Excavation, diagrams by Hoffecker (2002).

The presented project is the competition entry from the Georgia Institute of Technology, which was developed as part of a senior design studio. For the conceptual phase of the competition, the team's initial step was to determine an overall approach to the prompt. McDonough and Braungart (2002) explain in Cradle to Cradle that nature operates according to a system of nutrients and metabolisms, in which there is no such thing as waste; one system's waste is another systems food. Therefore, waste equals food. Humans, however, have found more and more ways to manipulate materials to increase their effectiveness in use, without considering their performance as waste. According to Braungart and McDonough these types of engineered materials have an abnormal conversion to base components and cannot safely be returned into earth's surface. Thus, in their view humans have created waste that cannot be converted to food. Sometimes these waste products are "recycled", which more accurately results in down-cycling – meaning the conversion of goods to lesser quality goods. The aim of Braungart and McDonough here is "not to reduce or delay the cradle to grave material flow but rather to create metabolisms that allow for methods of production that are true to nature and in which materials are used over and over again" (EPEA 2011).

In light of this, the students aspired to repurpose a waste product whether or not it could be "recycled". Some of the earliest precedents of repurposed mate-

rials are the mammoth bone huts built between 16,000 and 10,000 BC. The huts were 20 feet in diameter and made from interlocking mammoth bones. While bone huts were useful as dwellings, Marcel Duchamp repurposed items as art. The early 20th century artist created less than 20 "Readymades" in his lifetime, which were ordinary objects slightly modified and signed as art. This minimalist art exemplified the idea of reuse of ordinary materials at a time, when western industry was rapidly expanding. After a phase of initial investigations the team focused on two ideas linked to plastic as a material. The first idea was an amalgamation of modules of plastic clothes hangers. The second idea was a tapering cylindrical tower of plastic soda bottles, directly representing the amount of plastic waste by the university community over a given period of time. At the end of this phase it was decided to concentrate efforts on both ideas, bottles and hangers, to create a dual installation as competition entry.

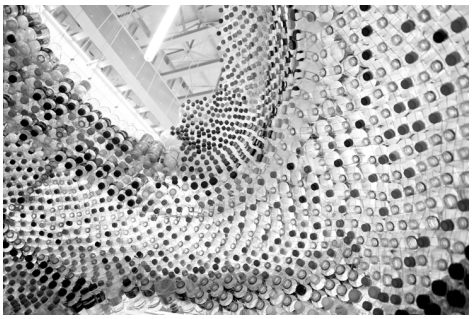

Figure 2. Bottle tower – interior view.

3. Theory and vision

Though both are made of polyethylene terephthalate (PET) soda bottles and clothes hangers have different means of consumption. On the one hand, soda bottles have become an icon of recycling and sustainability. They have increasingly become more recyclable, using lesser amounts of plastic per bottle, and they have even started using plant material to improve biodegradability of the bottles. Individual consumers use the bottles personally, and their recycling characteristics are often displayed prominently on the bottle. On the other hand, clothes hangers are used by private stores, which typically reuse the hangers. When stores receive new hangers, they amass old hangers, which are thrown out or sometimes, depending on the store, recycled. This consumption is hidden to the individual, unlike the consumption of the bottles, for which the individual is directly responsible. Given a single material with two starkly different stories of consumption, the team showcased the different physical

properties of the items through two installations as a parallel to the different modes of consumption.

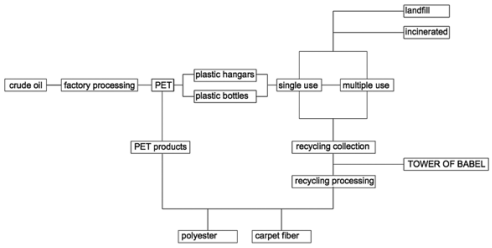

Figure 3. Diagram of PET product usage.

However, as different as the two installations are on a material level, they share a common vision of experience for a user. Each installation immersed the user amongst towers of waste generated by flawed human consumption patterns. The users were not only exposed to, but were surrounded by physical representations of their wasteful behaviour.

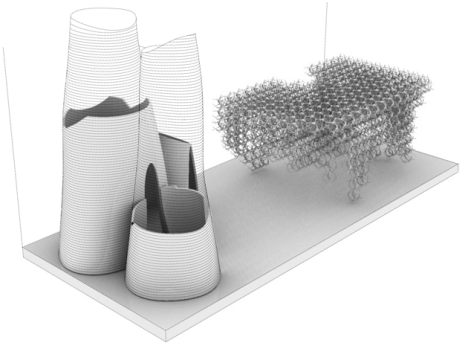

Figure 4. Tower morphologies: digital model.

4. Tower morphologies

The concept for the bottle installation was three towers composed of roughly the same amount of PET that the university community threw out, rather than recycled, in a typical week. The number is an estimate that is based on information gathered from the university's Office of Solid Waste Management and Recycling. Though it was a very rough estimate, the number of 19,000 bottles gives an idea of the enormity of waste produced by a campus in a week, which could be avoided, if individuals would dispose of them by using the existing recycling system rather than throwing them into the regular trash.

Capturing the enormity of waste in a physical form, the design of the bottle installation included three towers of different heights and widths, with the central tower being the largest at 25 feet tall and 15 feet in diameter. The tops of the towers undulated to give the appearance that the towers were not yet complete, representing the continuously amassing piles of waste in the region. The inhabitable towers worked together, forming a sequence of movement through them.

The hanger installation is conceptualised as a grid of inverted towers reaching down to various heights from a suspended surface. The 9 × 18 grid of hanger towers begins 12 feet high and the individual towers vary in length. The determined lengths and locations of the towers allow people to pass through the installation and observe the multiple densities of the plastic and prismatic affects that the hangers have on the light passing through. The fingers of towers hanging from above juxtaposed the bottles towers and immersed the observer among the clean, crystalline structure of the hangers.

The experience of waste as beautiful and pedagogically positions the project in proximity to current movements in sustainable architecture, which proclaim a hedonistic sustainability (Ingels 2010). One example is the waste management plant for Copenhagen in Denmark, which was designed by BIG. The plant incinerates waste for heat and electricity generation and provides a ski mountain with 3 different slopes with a total length of 150 m at the same time. According to Ingels the project demonstrates that "sustainability is not a burden" (Ingels 2010), that sustainability can be fun.

5. Materials/system design

5.1. BOTTLE TOWER

Greg Lynn's installation "Blob Wall" is one of the few installation that investigates recycling, digital design and fabrication at the same time. The "Blob Wall" is designed from recyclable plastic blob units, or "bricks", which are different from each other in the way that they attach to their neighbouring units. The variation lies in the intersection of two units.

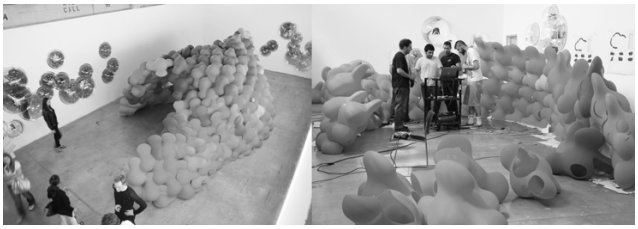

Figure 5. Greg Lynn Blob Wall 2008.

In the case of the bottle towers the variation results not from the units, but from the variation of the joints, of the in-between spaces. The system deforms through the gaps allowing for curvature in plan and tapering in elevation. But it also allows for transformation: When the diameter becomes too small, "bricks"/bottles are skipped. Also, the assembly system for the bottle towers is designed to showcase the visual material properties of the bottles without impacting their ability to be recycled after deconstruction. The bottles are arranged as circular courses of bricks laid horizontally with their caps pointed towards the centre. Each course is offset from the adjacent courses and therefore any individual bottle is supported by the two bottles below, essentially creating a running bond.

The bottles were sorted by label type and stacked in three rows of a given label; for example, three courses of Coke, followed by three courses of Diet Coke, followed by three courses of Sprite, etc. building the bottle towers as cohesive units up to 25 feet-high required proverbial mortar for the bricks of bottles. Through this pattern one could perceive some order in an otherwise chaotic aggregation of parts. The approach is similar to brick architecture of William Butterfield, also called the "Streaky Bacon Style", or, more recently, to the Historical Museum in Ningbo from Amateur Architecture Studio, where 20 different kinds of grey and red rubble stones and bricks, all repurposed materials, are used for the building skin. The material chosen to hold the bottles together without damaging them was elastic bands. This system created a network of lines that were more visible inside the towers, where the tops of the bottles faced, than outside, where the bands were more hidden by the bottom of the bottles. The bands allowed for easy disassembly and left the bottles in the same condition they were in prior to construction. While the elastic bands were favourable for a number of reasons, one drawback was that they did not create rigid connections, so the towers would tend to buckle under their own weight. To solve this problem, a system of 3/8" thick acrylic rings was CNC-fabricated and placed every 25 courses up the tower. The rings acted as structural straps that one typically sees on a brick tower to keep it from buckling.

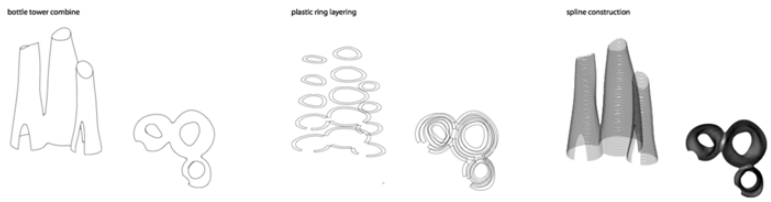

Figure 6. Fabrication matrix of CNC-cut rings.

5.2. HANGER TOWER

Four hangers formed the top “plane” of the cube, with 2 hooks reaching towards the outside and two hooks reaching towards the inside, and four hangers formed the bottom “plane”.

Figure 7. Hanger structure.

Combining the modules into towers involved interlocking the hooks with the neighbouring modules on the top and bottom respectively. The suspension of these modules created the towers. Where the modules of one tower aligned with the modules of another, the outside hooks were interlocked to provide further rigidity to the installation. Although this interlocking system had inherent structural integrity, plastic zip ties were used at every joint within the modules and towers as a whole, to bolster the strength and security of the system.

7. Parts fabrication

Construction of the bottle towers began with the plastic rings, which were designed to reflect the profile of the bottles. This also allowed the rings to act as a template for sandwiching courses of bottles: each profile in a ring would have a bottle banded above and below, establishing the number and placement of bottles in each course around the ring. The rings were divided into segments and cut on a CNC router. Each segment was labelled by script with its specific tower, course number, and placement within its ring.

After the ring segments were cut, prefabrication began. Each segment acted as a template for a panel of 25 courses of bottles. However, since the towers tapered towards the top, the upper courses required fewer bottles than the lower courses. A VB script, that populates a given Nurbs geometry with bottles, calculated the number of bottles needed for each layer. Assembly began according to the banding system as described in the digital file.

Prefabrication of the hanger installation involved creating the previously described 12-hanger modules out of the 6000 hangers collected. The modules were assembled first and then each joint was zip tied for security.

8. Reception

The installation was well perceived during the exhibition and during the following symposium "I imagine, I see, I make" in two ways: firstly it was appreciated, that the installations visualise the invisible by showing the amount of waste produced and secondly during the symposium the tectonics of the two structures were positively discussed with reference to current design methodologies in digital design that explore emergent systems with variation.

Visitors during the exhibition enjoyed the spatial experience and the aesthetics of the installations and were highly surprised by the enormity of waste. Unfortunately, the circumstances of the exhibition in an interior space made the installation only accessible to exhibition visitors and limited the access for the general public. A more public display would have benefitted the intention of the installation.

The proposal received the 2nd prize in the overall judgment and was placed 1st in 3 out of 7 sub-categories (creativity, presentation and coordination). One member of the jury, V. Sorenson, recommended the team in the following way: "The use of hangers and bottles is excellent. Bringing attention to the fashion industry's waste is creative and relevant especially to young fashion conscious students and therefore a good choice for a university setting. Relating the scale to amount of campus use is good. The tower designs are highly impactful, both as beautiful, aesthetic designs that can be studied and experienced from multiple physical perspectives, but also from multiple content and conceptual approaches..." (Tower of Babylon 2010). Another juror critiqued the emphasis on aesthetics rather architectural functionality.

9. Junk as building material

The two installations did not intend to focus on the invention of an actual building material or building component from waste products. But the investigation of that process is certainly interesting to study. There are a number of different examples for the re-use of materials: the rural studio projects in Alabama, that used tires filled with earth as construction material and carpets as a façade material, the re-use of bricks by Amateur Architecture Studio for the Historical Museum in Ningbo, the use of wood waste and car screens for the shoe shop Duchi by the Dutch office 2012 architecten and other examples (Kaltenbach 2010). But to discuss these project in details would exceed the

framework of this paper, therefore it seems appropriate to mention projects related to the installations: bottle houses. Early examples of bottle houses like Grandma Prisbrey's Bottle Village, a folk art piece in Simi Valley, California, use glass bottles and a binding material like cement, stucco, clay, plaster, mortar etc. to play with coloured light effects. The more recent projects use plastic bottles. There are numerous examples, where earth-filled plastic bottles have been used for the construction of passive solar houses as bricks (for example projects by Andreas Froese/Eco-Tec in Nigeria and Honduras). These projects are often situated in tropical climate zone and rural, less prosperous areas. Next to architecture in development countries we can find another example for a plastic bottle building in the EcoARK Exhibition Hall, Taiwan, by Arthur Huang, which uses the POLLI-Brick system by Miniwic. POLLI-Brick, made from recycled Polyethylene Terephthalate Polymer, is a system of interlocking, especially engineered bottles with improved thermal and sound insulation. Obviously, we are leaving the field of re-used materials with the POLLI-Brick and enter into the world of recycling products, which are highly engineered. Maybe that is necessary in order to develop a product from waste material, but it might be interesting to explore venues, in which a re-used material instead of recycled material could be modified with means of digital fabrication as a continuation of Greg Lynn's approach.

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DIGITAL AND PHYSICAL COMPUTING FOR INDUSTRIAL ROBOTS IN ARCHITECTURE

Interfacing Arduino with industrial robots

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Abstract. Customisation is one of the most important topics in architecture, as architects generally work on individual prototypes instead of mass-produced designs. By using customised design and fabrication tools, architects are able to individually respond to challenges, instead of relying on universal software tools. This paper proposes new software components for interfacing industrial robots with physical computing microcontrollers, thereby allowing the customisation of physical tools for industrial robots. By pairing physical computing with rapid prototyping, architects are able to design and prototype individual fabrication processes for industrial robots.

Keywords. Industrial robots; physical computing; interfaces; rapid prototyping; computer aided manufacturing.

1. Introduction

In recent years, architects have become interested in the topic of physical computing. Due to powerful and accessible integrated development environments (IDEs) such as Arduino, architects and designers are now able to prototype and program complex electrical circuits without the help of electrical engineers. A similar trend can be observed in the area of industrial robotics, where software written by architects is enabling a wider range of users to control robots out of affordable, architecture-centric Computer Aided Design (CAD) software. This development is not only driven by the desire to streamline the whole workflow or to reduce costs, but aims to free users from the constraints of current Computer Aided Manufacturing (CAM) software, by letting them

create their own parametric design and fabrication environments instead of having to rely on preset fabrication strategies.

However, being inherently multifunctional machines, industrial robots are very much dependent on their end-effectors, which often have to be custom-built by engineers for the robot's particular task. By using a physical computing platform for prototyping robotic end-effectors, architects and designers can create their own hardware tools for robotic fabrication and directly control the data-flow between the robot's control unit and any kind of external devices. Furthermore, this data flow can be reversed by attaching sensors to a microcontroller and sending the collected data to the robot, which then interprets it and reacts according to its programming. The following chapters will provide a brief introduction to industrial robots and physical computing and discuss existing work where non-standard robotic end-effectors have been used.

We will present a range of custom components for the parametric design software Grasshopper, capable of communicating with industrial robots as well as writing robot code for interfacing with microcontrollers. Using this interface, a KUKA KR5 robot can control custom end-effectors such as a 3D printed gripper and a modified airbrush spray gun.

2. Industrial robots

In the scope of this paper, the term "industrial robot" refers to robotic arms, or serial articulated robots, which are most commonly seen in the automotive industry where they are used for a wide variety of tasks such as spot-welding or spray-painting. This multi-functionality, which allows a robot to change from a milling machine to a 3D-scanner, just by switching its end-effector, along with its large working space and – compared with multi-axis Computer Numeric Control (CNC) machines – the affordable price, has sparked an interest of both the construction and creative industry in robotic arms.

In the past few years, architectural faculties at institutions such as the ETH Zurich, TU Vienna, University of Stuttgart and the University of Michigan have acquired industrial robots and are actively researching the use of robots in architecture. However, this research is not limited to academia, with architectural offices like Snøhetta in Norway using robots in-house.

The main challenge when dealing with industrial robots is to efficiently program their movements. Moving from CAD to a physical output involves a unidirectional workflow consisting of up to three software packages, in addition to the handling of the robot itself. (see Brell-Cokcan and Braumann 2010, Bechthold 2010). These issues encouraged the development of plugins such as KUKA|prc (Braumann and Brell-Cokcan 2011) and SuperKUKA (Pigram and McGee 2011), which integrate into software used for architectural design and

give users the possibility to plan and simulate the robot's movement within the CAD environment and to ultimately generate robot control data files that can be directly executed at the robot. By using these plugins, the user is no longer forced to work with predefined fabrication strategies, but can program individual toolpath scripts which are immediately transformed into robot control data by the robot-plugin. This approach has several advantages: A direct feedback loop when changes are performed to the initial geometry, allowing a more intuitive grasp of the action-reaction relationship, the possibility to automate the generation of robot control data for mass-customisation of elements and ultimately a much more affordable price compared to commercial CAM software.

However, the main goal of these plugins is to generate robot control data files that contain a sequence of positions – by default they do not create code that can interact with external sensors or actuators.

3. Devices and interfaces

It is necessary to find a common interface that can be accessed by the parametric design tool, the industrial robot and the microcontroller. In the scope of this paper, Grasshopper was chosen as the parametric design and robot control environment, Arduino as the platform for physical computing, and a KUKA KR5 as an exemplary industrial robot. Transmitting data between such different devices requires an interface to be as simple as possible, in order to reduce the margin for errors.

3.1. ARDUINO

The Arduino board is part of the Arduino environment, an "open source physical computing platform based on a simple input/output (I/O) board and a development environment that implements the Processing language" (Banzi 2008). Users write code in the well-documented Processing language and submit it via serial or USB port to the Arduino unit. Other interfaces like Ethernet are only available as hardware addons - the native and easiest way of communicating with an Arduino board is therefore via the RS232 serial port.

3.2. GRASSHOPPER

Grasshopper is built as a .NET application with groups of components contained in separate class libraries. The .NET framework includes several classes for interfacing with external devices, such as the SerialPort and UdpClient classes for serial and Ethernet communication.

3.3. INDUSTRIAL ROBOTS

All current control units for KUKA robots are based on common PC hardware. Therefore, they offer the regular range of connectivity, such as USB, Ethernet, serial, and parallel ports. However, while the underlying Windows operating system can access all these ports, not all of them are by default available to the robot application. Commonly used are only the Ethernet (Chinello et al. 2010) and the serial port (Maletzki et al. 2006). While the Ethernet port allows a more direct real-time control with less lag, it requires modifications to the control unit or additional technologies such as the RSI-XML Ethernet interface. On the other hand, the serial port can be configured within a single *.ini file and accessed via regular, well documented commands of the KUKA Robot Language (KRL), without requiring any expenses besides the RS232 cable.

3.4. SERIAL INTERFACE FOR INDUSTRIAL ROBOTS

We therefore conclude that a common interface for connecting parametric design software, Arduino microcontrollers, and an industrial robot in a low-tech/low-cost context has to be based on either the RS232 serial port or on Ethernet technology. According to Axelson (2007), serial communication adds only little extra information to each transferred byte, while Ethernet uses sophisticated protocols that define the format of transferred data. Aiming to keep both complexity and costs down, communication via the RS232 serial port (Figure 1) seems to be the best choice of interface.

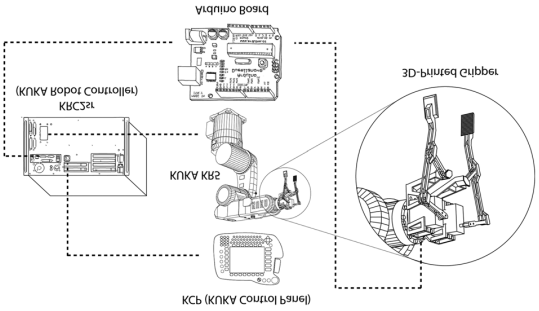

Figure 1. KUKA control unit sending data to the control panel, the robot, and an Arduino board, which controls a 3D-printed gripper.

4. Realised interfaces and non-standard end-effectors

The interfacing of external devices with PCs and industrial robots is mostly researched in electrical engineering and computer sciences, where these inter-

faces are used for robotic vision, pick-and-place systems etc. However, these systems are complex, specialised, and usually running on top of software such as MATLAB (Chinello et al. 2010), instead of design tools that are commonly used in architecture. The following overview is therefore limited to projects within an architectural context.

4.1. INTERFACES

In previous research, we developed KUKA|prc, a plugin for Grasshopper that is capable of creating robot control data files for KUKA robots (Braumann and Brell-Cokcan 2011). While a full kinematic simulation of the robot´s toolpaths is possible, this plugin does not directly communicate with the robot, as the control data files have to be sent to the robot before they can be executed.

Previous work on the topic of linking parametric design and physical computing has been performed by Andrew Payne and Jason Johnson who developed Firefly, a plugin that allows direct communication between the parametric environment and Arduino boards. Payne (2011) also presented a robotic motion controller for designers – basically a 5-axis digitiser with the proportions of an industrial robot, which sends its posture in real-time to Grasshopper, where it is turned into robot movement commands.

4.2. END-EFFECTORS

Standard end-effectors for industrial robots are e.g. gripper, milling spindles, and welding equipment. While these end-effectors have been involved in innovative projects in architecture, they are not innovative by themselves, as they have been used in similar form by the automation industry for many years. In the past years, the University of Michigan published several projects involving customised robot-hardware (Figure 2).

Figure 2. Robotic rod-bending (left), hotwire-cutting (middle), foam-depositing (right).

One such example is the wavePavilion by MacDowell and Tomova (2011), which was constructed out of three-dimensionally bent rods. Using a custom-

ised gripper, the robot placed the steel rods with the right position and rotation inside a custom CNC rod-bending device.

Several other end-effectors were also prototyped, such as a 2-dimensional roller cutter, or a foam depositing device, which was used to perform large-scale additive manufacturing. For the Periscope Tower, a hotwire cutter was mounted onto the robot, creating a multi-axis CNC hotwire-cutter capable of processing 4 m long EPS blocks (Pigram and McGee 2011).

None of the projects listed above mention the interface responsible for communication between the industrial robot and the end-effector. It therefore has to be assumed that industry-standard technology from automation such as a fieldbus protocol was used, requiring proprietary controllers.

5. Bidirectional robot control

State of the art IDEs allow architects to program software and control applications without knowledge from automation. Instead of taking fieldbus courses aimed at robot technicians, designers can duplicate the relevant part of the functionality in the Processing language and send it to the Arduino board, which then manages the communication between the device attached to its serial port (i.e. the industrial robot or a PC) and its actuators and sensors. Similarly, using environments such as Microsoft Visual Studio, architects can build their own interactive design-tools.

The software developed for this paper is a range of four custom components for Grasshopper, integrated into the KUKA|prc plugin. They are written in C# using Visual Studio, the Grasshopper SDK and the RhinoCommon framework. These components can be divided into two groups: Real-time components that allow the user to *send* position and other information via the serial port in (near) real time from the parametric environment to the industrial robot, as well as *receive* data in real-time from the robot. The second group is movement planning components which create robot toolpath similar to KUKA|prc, but insert additional information that operates external devices by sending data from the robot's serial port to the Arduino board (see Section 6.2).

5.1. REAL TIME COMPONENTS

Three components belong to the group of real-time components (Figure 3c): First, there is the *Serial Setup* component. After setting the correct COM port and baud-rate, the component opens a connection to the serial port and locks it for all other applications. Furthermore, a graphical user interface (GUI) is available, where the user has to set the robot's local coordinate system, the mounted tool and the robot's serial port. Using this information, the component can generate three types of robot control data files: One that prepares the

robot for receiving Cartesian position data in XYZABC format, one for receiving axis rotation values in A1–A6 format, and finally one control data file that continually transmits the robot's current axis rotation values to Grasshopper.

If the program running in the robot's control unit is transmitting its current axis values, the *Serial Receiver* component in Grasshopper can access the data from the serial port and send it to a forward-kinematic solver which instantly shows the robot's current posture inside the CAD environment. Therefore, the parametric environment is always aware of the current position of the industrial robot and can e.g. disable/enable devices whenever the robot enters a defined area of its workspace. The *Serial Send* component is used whenever the robot is set to receive position data via the serial port. This component accepts either the coordinate frame of the end-effector or the rotation values of all six axes and sends that data in either XZYABC or A1A2A3A4A5A6 format via a serial connection to the robot. Once the robot has arrived at the transmitted position, it stops until it receives the next set of position values. Simulation inside the parametric environment is possible by connecting the position data to the kinematics solver.

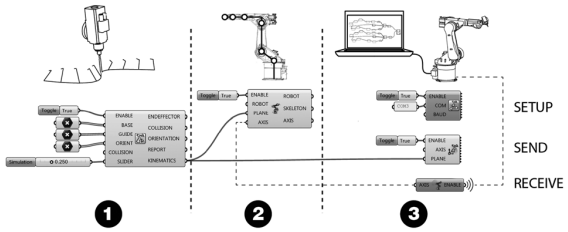

Figure 3. Parametric real time control workflow: Toolpath generation (a), forward/inverse kinematic solver (b), Serial Send/Receive components (c).

5.2. OFFLINE COMPONENT

The fourth component works differently, as it does not send data in real-time, but generates robot control data files similar to KUKA|prc, but containing *both* movement and serial commands (see Figure 5). As an input, it accepts lists of curves, representing tool movements, which get divided into three sets of points. Each triplet of points can then be expressed in XYZABC and written as a movement command into the KRL file. In the GUI the user chooses a start command and an end command which is sent from the robot to the Arduino at the beginning and end of each movement. This process can be used for a wide variety of tasks, such as welding, additive manufacturing or spray painting, where a device has to be continually enabled and disabled in between tool paths.

5.3. SCALABILITY OF CODE

It is important to note, that the components outlined above are not unique to the KUKA KR5, but generate code that is compatible with nearly all KUKA robots. This "scalability" of code is one of the greatest advantages of robots compared to conventional CNC machines, as it ensures that code written for a compact KUKA robot can also be executed on the massive heavy-lifting KUKA Titan. This enables the concept of "fabrication prototyping", where fabrication processes can be tested on small scale robots, before moving on to full scale production.

6. Exemplary Applications

6.1. REALTIME CONTROL IN TEACHING

The realtime components described in Chapter 5 were used to realise a near real-time control of the robot from a touchscreen device. This was done to provide students with a more direct interface to the robot's kinematics, as they feel much more comfortable with a tablet device than with the intimidating KUKA control panel. TouchOSC, a commercial iPhone-app for DJs was adapted to provide six numeric sliders, one for each axis, which provides the input for joint coordinate programming. These values are sent over the wireless network and captured by a Grasshopper component. Another small custom component then divides the data back into six axis values and transmits them to the Serial Send component, which passes them with a checksum to the robot. While the lag is considerable and only one axis can be moved per transmission, students were able to much more quickly get a grasp of the robot's kinematics.

6.2. ARDUINO-CONTROLLED END-EFFECTORS

Our Arduino-control component was tested with custom-built end-effectors at a two-day robot workshop with both professional architects and students.

For a pick-and-place application, we developed our own, kinematic gripping device in the CAD software Rhinoceros and had it prototyped for 80USD via selective laser sintering (Figure 4, left). The physical model was then equipped with two servo motors, mounted on the flange, connected to an Arduino board and put into action. As programmed in the Grasshopper definition, the robot moved to the first point, sent a serial command containing the desired position of the servo motors for closing the gripper (e.g. "40") and then moved via a safety distance to the end point, where the gripper released ("0") the object again. A second iteration of the gripper, constructed out of

laser-cut acrylic class and again equipped with two servo motors, proved to be both cheaper and more robust than the SLS version (Figure 4, right).

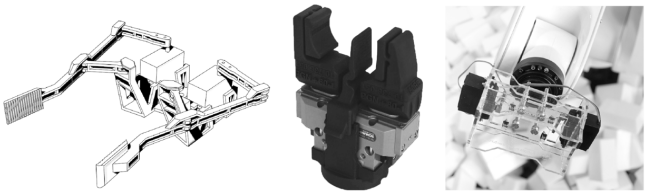

Figure 4. 3D gripper model for rapid prototyping (left), commercial gripper with 3D-printed jaws by Schunk (middle), acrylic-glass gripper mounted on KR5 (right).

Robotic graffiti was performed with the tool path generation component. By hacking an airbrush compressor it was possible to enable and disable the compressed air using a relay and an Arduino board. At the start of each spray painting tool path, the Grasshopper-generated KRL file sent a serial command to the Arduino board, enabling the compressed air, and at the end shut it down via another serial command (Figure 5).

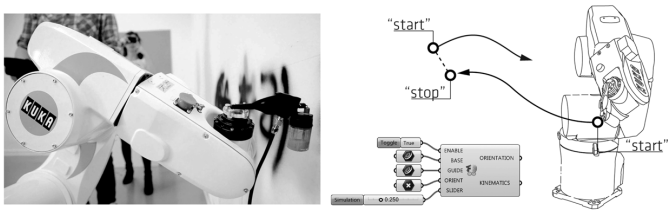

Figure 5. Robotic spray painting (left), spray painting process scheme (right).

7. Conclusion and outlook

This paper represents another small step towards a more open and adaptable system for the design and fabrication with industrial robots. Projects such as the KUKA|prc tools prove that it is possible for architects to develop their own digital design tools to control and optimise robotic fabrication. The approaches presented in this paper show that this control does not have to be limited to the software side, but can also be extended to the hardware side, thanks to accessible IDEs such as Arduino.

We imagine, that in the near future architects will not only program industrial robots, but will soon learn from the automation industry to further develop their own physical tools. Custom digital and physical tools brought together will allow architects to control fabrication of mass customised parts, assembly and mounting alike.

In the scope of this paper, customised end-effectors were used for researching possible low-cost approaches towards linking physical computing with industrial robots. The topic of rapid prototyping for highly customised end-effectors is already relevant for industry: Just recently, the automation supplier Schunk introduced a gripper system that uses 3D-printed, custom designed jaws that are modularly mounted on a standardised gripper module (Figure 4, middle). In the near future we therefore see physical computing paired with rapid prototyping as an accessible and powerful tool allowing architectural practices and universities to gain an active role in researching full scale industrial robotic processes. The scalability of code will ensure that the concepts developed in this paper can be used for the full range of industrial robots, from KUKA KR5 to KUKA Titan.

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DIGITAL TO PHYSICAL

Comparative evaluation of three main CNC fabrication technologies adopted for physical modelling in architecture

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Abstract. Recently, digital fabrication, being a logical extension of computer-aided technology to the material world, was introduced into the field of computational design in architecture. The objective of this experimental study is to investigate and systematise data regarding the production issues and limitations of the main Computer Numerically Controlled (CNC) fabrication technologies adopted for physical modelling in architecture. This study also aims to observe the value of potential feedback to the design process from different types of digitally fabricated architectural models. This experimental research systematically explores digital fabrication as a computer-aided modelling tool, using two international architectural competition projects as case studies: the design of a skyscraper and relocatable schools. Developed by authors especially for this research paper, each case study acts as a test bed to compare and evaluate digital production techniques adopted for physical modelling in architecture. Designs go through a process of refinement using CNC fabrication as an integral part of the design process. Each step in the process is closely evaluated as to its effectiveness according to a matrix of feedback criteria.

Keywords. Design process; digital fabrication; architectural model.

1. Introduction

This paper documents a systematic exploration of the potentials of digital fabrication within the architectural design process. A simple typology of digit-

ally fabricated physical models is applied systematically to two design case studies. The result is a reflection-in-action documentation of the role of materialised virtuality in the architectural design process.

Digital design in architecture progresses as the architectural model progresses. Architects use models as a thinking and defining mechanism for understanding and presenting architectural ideas (Smith 2004, p. vi). With rapid technological development in the field of CNC fabrication, computer-aided design has evolved from pure virtuality to a more complex tool, which blurs the boundary between matter and space (Andia 2001).

2. Physical model typology

Three functional types of physical model were defined for this study: conceptual, working and presentation phases (Arpak 2008).

Conceptual models can be understood as intuitive spatial translations of parameters as varied as the abstract idea. Whilst lacking in physically explicit detail, they can be rich in symbolic content (Downton 2006).

Working models are used as an experimental platform, a tool which informs the design. Working models typically have relatively complex, explicit details of both form and construction (Porter and Neale 2000, p. 21).

Presentation physical models are high-performance instruments for representing final, detailed project solutions in architecture (ibid).

3. Alternative production techniques of digital fabrication

The technology of digital fabrication is rapidly changing. Architects are adopting wide varieties of CNC manufacturing facilities. This materialised virtuality research focuses on three clearly distinct technologies: laser cutting, CNC routing and 3D printing (Kolarevic 2003, p. 31).

4. Case studies

In order to ensure the brief and design goals were independently defined and thus had little influence on the study, two international architectural competition projects were selected as case studies of the application of the three technologies. Physical modelling via digital fabrication was integrated into the design loop at key stages of the project development.

4.1. CASE STUDY AUSTRALIAN FUTURE PROOFING “SCHOOL” (2011)

The conceptual model in this case study explored the spatial relations of two triangular patterns. One of these patterns represented school modules and the other – a canopy system (Figure 1, conceptual model).

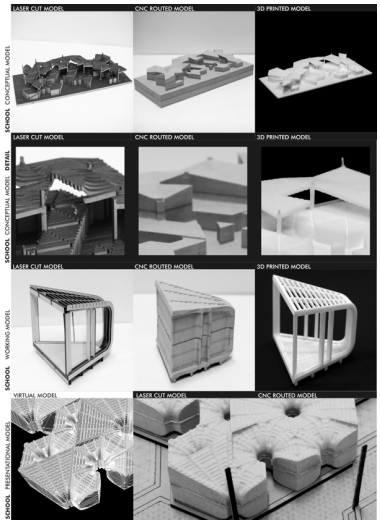

Figure 1. Matrix of model: CNC fabricated School model.

In response to the brief requirement for modularity the conceptual digital model was defragmented into basic functional components. The intention of the working design stage was to develop an easy to assemble, relocatable module structure and to explore possible connections and clustering combinations of different types of modules. Scaled prototypes of the main modules were fabricated to test the design solution (Figure 1, working model).

A strategy of separating manufacturing processes was used in order to explore the possibility of fabricating different parts of one virtual model with alternative techniques, and thus engage various materialisation processes to manufacture one single object (Figure 1, presentational model).

4.3. CASE STUDY “TOWER” - EVOLO (2012), SKYSCRAPER COMPETITION

The main objective of the conceptual tower model was to explore formal and spatial qualities of the case, when two different spatial logics interpenetrate into one single volume (Figure 2, conceptual model). Physical models, fabricated for the conceptual stage of this case, revealed the fact that the initial approach of interpenetrating groups of spatial elements was not successful. Tectonic differences between different types of objects (extruded hexagon and boxes) were hardly distinguishable. As a result the design strategy shifted towards surface patterning.

The main objective of the working tower model was to test the formal qualities of the proposed “building skin”. It consisted of a gradual blend of

two symbolic patterns, evaluated according to the level of articulation created by each pattern type (Figure 2, working model).

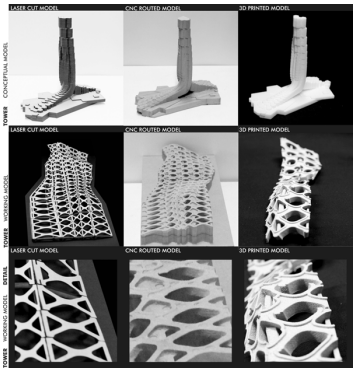

Figure 2. Matrix of model: CNC fabricated Tower model.

5. Evaluation criteria

Each digitally fabricated model was evaluated according to key performance criteria for "input – process – output". The system of criteria was divided into two groups: the first group explored the influence of the technologies on the design process: the interaction or interference between physical and digital models; the second criteria group aimed to evaluate practical issues of CNC fabrication and focused on the following parameters:

- Time spent on digital model preparation, fabrication, and completion (human work / machine work)
- Cost of material and work
- Human contribution to the process of physical model production

The average time spent on model development and the average cost of each type of CNC fabrication technology are documented in Table 1. The following comparison chart shows the proportional time breakdown between human work and digital fabrication.

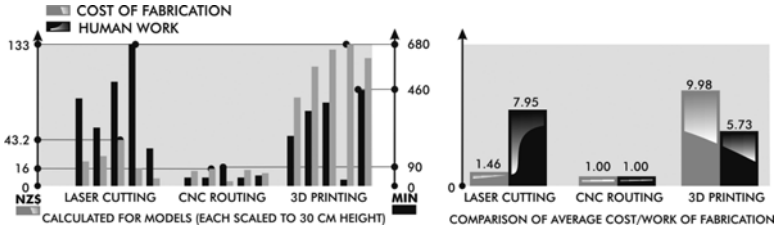

Figure 3. Comparison chart (based on experimental data) of model fabrication.

TABLE 1.Digital fabrication data.

LASER CUTTING		Conceptual model		Working model		Presentation model
		School	Tower	School	Tower	School
Equipment		Universal Laser systems V-460				
Pre fabrication development	min	180	200	220	320	60
Laser cutting	min	90	120	120	160	30
Assembling	min	240	90	280	360	120
Model dimensions x/y/z	cm	30/ 12/ 4	30/ 25/ 30	25/ 25/ 25	60/ 32/ 15	40/ 35/ 8
Cost of material	NZ$	8	8	16	8	4,5
Cost of work	NZ$	15	20	20	25	5
Total time	**min**	**510**	**410**	**620**	**840**	**210**
Human work		**420**	**290**	**500**	**680**	**180**
Total cost	**NZ$**	**23**	**28**	**36**	**33**	**9,5**
CNC ROUTING						
Equipment		Modella MDX-40A				
Pre fabrication development	min	10	10	60	10	20
Setup of material /assembling	min	30	30	30	30	30
Milling with 6mm drill	min	840	1020	1200	1680	1440
Model dimensions x/y/z	cm	30/ 12/ 4	30/ 25/ 30	12/ 12/ 12	30/ 16/ 7	30/ 18/ 4
Cost of material:"Trimax"	NZ$	14	16	11	15	12
Total time	**min**	**840**	**1060**	**1290**	**1720**	**1490**
Human work		**40**	**40**	**90**	**40**	**50**
Total cost	**NZ$**	**14**	**16**	**11**	**15**	**12**
3D PRINTING						
Pre fabrication development/ fixing of rejected model	min	200 40	360 0	330 70	30 0	360 100
3D printing and delivery	NZ$	19,90	19,90	19,90	19,90	19,90
Model dimensions x/y/z	cm	10/4/2	9/5/8	8/8/8	24/7/5	7/6/3
Total time (with delivery)	**day**	**11,2**	**11,3**	**11,3**	**11**	**11,7**
Human work	**min**	**240**	**360**	**400**	**30**	**460**
Model cost	**NZ$**	21,09	31,19	29,60	91,2	56,59
Total cost		**40,99**	**51,1**	**49,5**	**111,1**	**76,49**

6. Reflection on model fabrication issues and feedback to the initial design

6.1. LASER CUTTING

One of the most distinctive characteristics of laser cutting technology used for physical modelling is that it operates in a two-dimensional spatial framework,

while “architects and engineers can aim to design mainly in 3D” (Corser 2010). Two very different strategies for translating a 3D model into a 2D set of elements were identified. One is to interpret a volume as a shell or envelope, subdivided into a set of connected outer surfaces - a logic similar to panelling tools in Rhino (Rhino Tech 2009). This strategy was adopted in the school working model. (Figure 1, working model)

The second strategy was implemented in the Evolo tower’s envelope models (Figure 2, working model). This treats a 3D volume as a solid structure. Here a 3D model is translated into a number of flat sections, outer contours made layer by layer through the volume in a chosen direction. Each fabrication method imposes a rigid mode of thought and a design interpretation that shifts the design from its virtual origin.

The panel approach adopted for the School working model led to its being developed as if it was to be realised onsite for a full scale construction (Figure 1). Design strategies became constrained by the technology to a logic that mirrors production approaches used in the building industry. Laser cutting involved a lot of pre and post fabrication work (Table 1).

6.2. CNC ROUTING

CNC routing has certain limits in terms of precision, material hardness, and particular difficulties in performing undercuts. It is problematic for CNC routers to fabricate sharp inside corners; these will always be filleted by the drill diameter. (Figure 1, 2, details). Parts and details located at a distance less than a drill diameter from each other were merged in the case study models into single volumes. As a result of these production issues, CNC routed models distinctly differed from virtual sources. They were a more abstract and less detailed volumetric translation of the concept than a digital model. These limitations turned out to have certain advantages.

CNC routed conceptual models supplied the most valuable feedback to the initial design. Being to a high degree an abstract and undeveloped representation of the idea, they allowed multiple readings and interpretations, providing a platform for visual formal and creative discoveries. The individual school modules merged when CNC routed, shifting focus from the modules to the whole. In the tower project model observation suggested that envelope patterns should be remodelled in order to emphasise the planned distinctiveness of the two underlying conceptual surface patterns that were to be combined in the tower.

6.3. 3D PRINTING

3D printing technology requirements stated that a virtual model should be converted into a watertight, manifold and less than 1,000,000 polygons mesh. 3D printing requirements also limited minimal wall thickness and detail level (Shapeways 2012). Some of these parameters can be automatically checked and fixed within the majority of modelling software. Unfortunately not all modelling programs have a built-in minimal wall and detail thickness detector. The only option with the modelling software used for this study was to measure all distances manually. This is doable when a model is simple, but as a model gets more developed and complicated, this task seems to be less and less achievable.

The issue of minimum detail level is very important, because the size of the model directly influences its cost (Table 1, cost). As designers reduce model size to achieve affordability, production limitations force simplification and generalising of fine details. The cost of 3D printing directly depends on the amount of material used, so model dimensions not model weight matter. To fabricate larger volumes, solid objects have to be remodelled as thin shell surfaces. This results in additional prefabrication modelling, which even for the experienced user is time-consuming, especially in cases when the model is complex (Table 1, human work).

7. Discussion

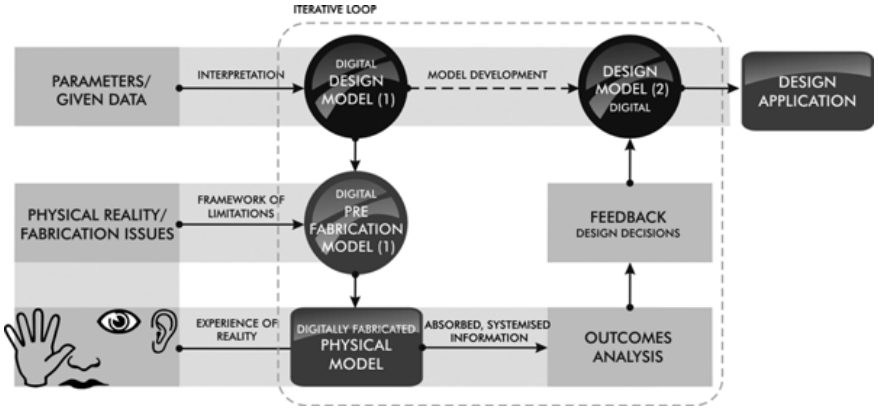

Figure 4. Model cooperation within design process (based on "Data and process model cooperation" diagram by Toth et al. 2011).

The success in these two cases of the integration of digitally fabricated physical models into the iterative design loop of a computer aided design process

(Figure 4) encourages the conclusion that materialised virtuality has a positive contribution to make in digital design. The case study physical models shared exactly the same digital code as their source virtual model, but were realised in the realm of physical reality. Each fabrication technology had its own unique influence on the different stages of a project's development. In each case it was the manufacturing constraints of the different modes of fabrication that influenced the role of the physical model. For example, for the ideation process, the imprecise CNC routed models were not only effective, but also efficient. The efficiency arose because the models were fabricated with minimal prefabrication development, which led to a fluid and fast ideation process. The roughness and approximation of details of the outcome model was an advantage, because the potential multiple readings of form suggested alternative design solutions (Figure 2).

The laser cut physical model proved to be an efficient modelling tool for the development and improvement of structural design solutions, though it was not yet a 'total building' solution" (Burry 2002). The school working model laser cutting pre-fabrication has encouraged the development of the module prototype, which was successfully used for the competition design proposal (Figure 1). The approach adopted for the use of the laser cutting technology stimulated engineering and material-based thinking.

Both CNC routing and 3D printing were successfully used for fabrication of solid volumetric models. Though those technologies allow fabrication of separate elements and parts, they do not necessarily require the development of a detailed structural solution (Figure 2). 3D printing claimed to be a powerful technology, which could accomplish the most precise, developed and complex designs. In practice, it was extremely hard to use 3D printing for elaborated models. The more complex and detailed a model gets, the harder it is to fix mesh issues before printing. The time spent on 3D printing prefabrication dramatically increased when the model was detailed (Table 1, Figure 3). The manufacturing and cost constraints force a choice between a small, very much simplified model or a large and expensive model. At the moment 3D printing is the most expensive technology (Figure 3).

8. Recommendations

During concept design, when form and detail are not fully defined, CNC routing could be an appropriate choice of digital fabrication technology. It requires minimal investment of time, skills and money (Figure 3.).

The large investment of time into pre and post fabrication development of a laser cut physical model was found to carry an added benefit that it can assist in the development of real world structural design solutions.

For all three physical modelling technologies, there is no simple equivalent to the print now button of 2D 'printing'. Even an experienced CAD user should be prepared to spend a significant amount of time on mesh fixing and thicknesses checks, especially if the model is complex and detailed. All models in these case studies had to be significantly changed or completely remodelled in order to meet all the requirements of 3D production.

In the 2D world it took some time before the constraints of the printing technologies were incorporated into the virtual world resulting in the What You See Is What You Get (WYSIWYG) representation mode. this paper has shown there are settings from drill bit size in CNC routing to wall thickness in 3D printing which could beneficially be incorporated into virtual modelling software in architecture, as it already is ink Industrial Design. The constraints of model abstraction are less easy to solve 'in software' but are no less influential on final design outcomes. The future of this study is best illustrated in the flat panel school and stacked pancake layer tower approaches to the user of laser cut technology. Neither approach is the best. Each hugely influences the design.

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BUILDING THAILAND'S TALLEST GANESH

CAD/CAM integration in conventional metal fabrication

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Abstract. Ganesh (Ganesa or Ganesha) is a Hindi god well known for his distinguishable elephant head and widely revered as the god of success or remover of obstacles. Patrons in Thailand have worshipped Ganesh and respected him by means of erecting statues of Ganesh in various poses and sizes throughout the country. In late 2008, the people of Chacheongsao, a province located East of Bangkok, decided to create Thailand's tallest standing Ganesh statue made with bronze reaching heights up to 39 meters and situated on the Bangpakong river bank overseeing the city and its people. The author and design team was approached by representatives from Chacheongsao and commissioned to advise the process from conception to construction. The challenge started with seeking appropriate computer-aided design and manufacturing technologies and innovative processes to guide the design team throughout the production. The 0.60-meter bronze cast sculpture of the Ganesh was scanned using a 3D optical scanner to generate a solid model of the statue. A surface model was then extracted from the 3D model to firstly determine the most efficient structural support within the statue and secondly to generate surface strips for the foundry to create actual bronze casts. The construction of the project began early 2009 and the statue has since been erected from its base to currently its head. During construction, the author and design team has encountered several problems translating pixels to parts. Several errors have occurred during the mould and cast production process as well as construction errors on site causing mismatches of the structure and surface, misalignments, and protruding structural supports and joints. The lessons learned from this project is documented and analysed with hopes to create a more effective process for future projects with similar requirements.

Keywords. CAD/CAM; 3D scanner; CNC milling; metal fabrication.

1. Introduction

Ganesh, a Hindi god well known for his distinguishable elephant head, is one of the most recognisable gods in the ancient world. He is widely revered around the world as the god of success or remover of obstacles, which has made him one of the most respected and worshipped gods today. The popularity of Ganesh in Thailand is also very prominent and consistent throughout the Thai society. Not only has Ganesh become the symbol of success and good fortune for Thais, he is also known for his skills in arts and performances and is symbolised in many governmental organisations and educational institutions.

Patrons in Thailand have worshipped Ganesh and respected him by means of erecting statues of Ganesh in various poses and sizes throughout the country in beliefs that Ganesh will bring upon good fortune and prosperity to their community. Because of this belief, The Chacheongsao Association, a local group led by retired government officials in the Chacheongsao province, decided to commission the construction of Thailand's tallest and the world's largest bronze Ganesh statue on the riverbank of Bangpakong river which runs through the heart of the province.

The project began in early 2009 as a public park on a land plot of 21 Rai or 33,600 sq-m adjacent to the Bangpakong river. The proposal was to house several functions including a museum of the people of Chacheongsao, an open marketplace for local farmers and tourists, and a 39-meter bronze statue of a standing Ganesh and its shrine.

Figure 1. The Ganesh park proposed by the Chacheongsao Association in 2009.

The project began with the master plan design of the park and a competition of the Ganesh statue design. However, for purposes of the author, this paper will only discuss the Ganesh statue and not other parts of the project. During the competition, several designs were submitted to the competition committee and finally a winning Ganesh statue was selected. The winning design was a Ganesh in a standing pose with its left foot placed slightly forward. Adjacent to its left foot is a rat holding food near its mouth, a symbol that represents the

abundance of produce and a plentiful harvest for the community. Its four arms also hold four types of harvest namely a banana, a sugarcane shoot, a jackfruit and a mango.

Figure 2. A bronze prototype of the winning Ganesh statue design.

2. Project planning

Planning of the Ganesh statue was divided into two phases; the first phase was to construct the statue and its base, and the second phase was to construct the surrounding buildings and the landscape.

Due to the size and complexity of the statue design that was intended to be the tallest bronze Ganesh in the world, the committee needed to consult with local experts in construction and metal fabrication industries to plan how to best proceed with this design. Presently, many tall statues have been erected around the world ("List of Statues by Height" 2012) but at the time, no one in Thailand had attempted to build any standing statue at such height before. So the first challenge was to identify the design and construction team that had experience and was capable of completing the task on time. The Chacheongsao association finally decided to bring in three main parties; structural engineer Assist. Prof. Pramote Tarasak from Silpakorn University to design the Ganesh internal structure and foundation, Asia Fine Art foundry based in Ayuthaya to cast the bronze Ganesh surface and construct internal steel structure, and Triple T Industrial Engineering, a local construction manager to oversee the project during construction. The author was part of the structural engineer team to design the steel structure support for the statue.

Construction schedule was limited to two years with a budget of 100 million baht or approximately US$4 million. The design of the structure was planned for three months and construction was to begin immediately after the foundation drawings have been completed. However, with the limited resources and seasonal floods during construction, the completion date had been pushed

back further and funds had run dry shortly after a year. Luckily, additional funds were raised by means of public donations in ceremonies throughout the year and construction continues as of October 2011.

2. Digitising

The main task of the structural engineering team was to design a steel structure that will fit inside of the Ganesh form and support the weight of the bronze surface as well as to withstand local wind load and rain load. What the team needed was an accurate digital model of the Ganesh statue to be used as a reference when designing the structural support from inside out. The most effective solution was to conduct a 3D scan of the 60 cm. bronze prototype provided by the winner of the competition and create a 3D model of the statue in a CAD environment. The team decided to use a 3D optical scanner due to its accuracy in scanning certain blind spots or hidden surfaces of the statue that laser scanners may not be able to pick up effectively.

Preparation for the scanning process required several markers to be placed on the surface of the statue at approximately every 5 cm radius and a layer of white non-glossy spray paint throughout its surface to prevent any reflections during the scan. The scanner captured several images around the statue in 360 degrees projecting simulated vertical and horizontal lines alternately to generate 3D coordinates at each intersection. The scan also required additional overlapping projections of the surface at certain blind spots such as the areas between the four arms, behind trunk, and under the groin that required further data clean up after the scanning was complete.

Figure 3. Preparation for 3D scanner with markers and white non-glossy paint on the surface (left) and scanning in progress by projecting vertical and horizontal lines alternately (right).

The scanning took three consecutive hours to complete and the manual data clean up took another two days. The result was an accurate and detailed surface model of the statue that could be exported in many standard 3D formats (i.e., DXF, STL, G3D, IGES, ASCII) and imported into 3D modeling software or

CAD applications. The volumetric triangulation of the surface created a total of over 640,000 polygons faces which most likely was too much information for the purpose of designing an internal structure or simply an overkill for the task. However, the data was used to determine the total surface area and the approximate weight of the bronze surface at 5 mm thickness for calculating dead load support.

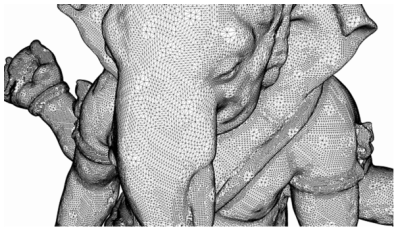

Figure 4. The triangulated surface model generated by the scanner.

3. Modelling

The 3D model generated by the scanner was then imported to a CAD environment, namely Google's SketchUp software, to explore the maximum allowable space to fit in a steel structure. The model was scaled to fit the actual construction size at 30 meters from the Ganesh's toe to his halo pinnacle and aligned at the 0,0,0 coordinates from the centre of its round platform beneath the feet. The 9-meter square base was not included in this design but was considered a shell that would cover the steel columns protruding from the statue's feet. To determine what type of structure to best fit the statue, the engineer decided to take the simplest approach and create outlined horizontal slices of the statue at every 50 cm heights. The profiles revealed the available gaps between the 5-mm bronze surface and the main support structure and therefore allowed the engineer to design a steel truss within the void.

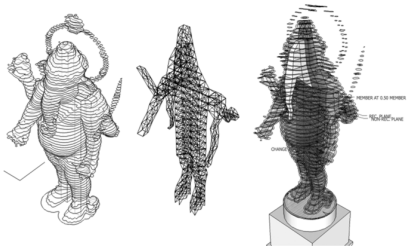

Figure 5. 3D model of the Ganesh in SketchUp with sections at every 50 cm height (left), the designed structural steel truss (middle), and the combined sections and structure (right).

The engineer designed a simple and practical steel truss structure to lessen the complexity during construction for the contractor. Each steel member of the truss comes in five sections only and has a horizontal member at every 1 m height. The spacing designated for the sub-structure for the bronze surface to connect to the steel truss is a minimum of 25 cm at its tightest gap which is located at the ankle of the right leg. This space will allow construction workers to manually connect the bronze bolts from the inner surface with the steel nuts located on the steel truss structure. The actual bronze surface of the statue is fabricated at the foundry in sheets of 1.50 meters tall and is hauled to the site to be assembled manually.

One of the main advantages of digital modelling in design is the possibility of early error detection before construction (Henderson 1999, Lertsithichai 2002). The Ganesh statue in 3D was a crucial tool in that sense to discover problematic structural joints that can be detected before the actual construction and assembling begins. The critical joints include all protruding structures that overhang from the main body such as the four arms, the trunk, and the halo ring. For practical reasons, these joints require special planning especially during the assembly because the parts would be constructed with a steel structure inside the bronze surface before hoisting the parts to be combined with the main body.

4. Fabrication

There are various rapid prototyping methodologies that have been developed and transferred into the manufacturing process and then employed by various industries including construction and metal work fabrication (Schodek et al. 2005). Such techniques were also used during the fabrication of the bronze surfaces of the Ganesh statue, mostly the laser scanning and CNC milling of the body parts and was conducted completely in-house by Asia Fine Art foundry.

The fabrication process at Asia Fine Art foundry usually starts with a wax replicate of the statue, in this case, a 60 cm tall wax Ganesh. The statue is measured and cut into small flat pieces that can be scanned with limited depth using a laser scanner (FROGScan). For example, a leg part is cut in horizontal slices about 20 cm high then cut again vertically into four parts. The four parts will be laser scanned to create a surface model of each part. Then the model is scaled up and transferred over to the CNC milling machine (FROG-Mill) to cut a foam piece of the part in real scale. The maximum area of the milling machine bed is 1.50 × 2.40 meters and it can mill up to 0.90 meter in depth. Once the foam sections are milled, they are covered in a wax surface to produce a sand mould for casting bronze. The mould is heated to release the

melted wax leaving a void for melted bronze to be poured in hence creating a perfect duplicated bronze surface of the part. This process continues until all the surfaces of the statue are produced, finished, and ready for assembly at the construction site.

Figure 6. Wax replicate of the Ganesh prototype ready to be scanned (top left), the scanned parts milled on the CNC milling machine (top right), the foam part milled into an actual sized toe (bottom left), the combined foam parts ready for a wax mold (bottom right).

5. Construction

From the 3D model generated in SketchUp, a set of 2D construction drawings complete with reference points and detailed steel joints were produced with AutoCAD and submitted to the steel contractor. The model was also used to calculate the weight of the bronze from its surface and the weight of the steel truss from the total length of each steel member totaling at 37 tons and 100 tons consecutively.

The construction of the foundation began in mid 2009 and the steel structure began shortly after. The construction manager present at the site saw no signs of concerns until the first set of bronze surfaces were ready to be assembled on site around the steel truss. The challenge they faced was to locate the reference point and align the surface to the right place with no guiding documentation. Since the construction drawings did not include segments or the actual bronze parts that were to be attached to the structure in the same drawing, it was difficult to pin point with accuracy how the parts were to align with the existing steel truss. The contractors solved the problem with a simple eye reference to the prototype statue and estimated the location of the part near the steel truss which at the time did not appear to become a major problem until later.

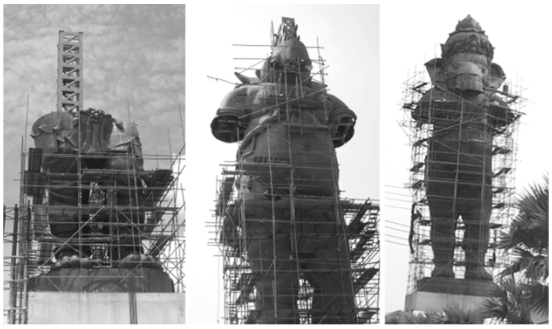

Figure 7. Construction of the Ganesh statue in mid 2010 (left), the body completion in early 2011 (middle), and the statue at its current state in October 2011 (right).

Construction continued on with delays and many on-site problems, mainly due to the fact that the steel contractor lacked the expertise in steel fabrication and did not comply with the structural drawings given by the structural engineer. The construction manager encountered at least three areas where the steel truss will protrude out of the bronze surface which required the steel contractor to cut parts of the frame and the foundry to patch the surface manually. Alignment of the bronze surface parts was also an issue that caused more on-site customisations, requiring foundry workers to work on patching the gaps along side with steel contractors as they build the structure.

Figure 8. Construction defects due to poor craftsmanship and lack of expertise: protruding steel structures at the thigh (left) and misaligned bronze surface at the hip (right).

6. Problems and lessons learned

6.1. SHARED DIGITAL MODEL

Ideally, sharing a single digital model of the statue between the structural engineer and the foundry would have cause far less errors during fabrication. The process of scanning and milling parts then reassembling them into a

larger part was prone to small errors that when combined would create large defects. A shared model could have been used to double check the sizing and alignment of the parts when attached to the structure to make sure that each section is well aligned before a new part is placed above.

6.2. POOR CRAFTMANSHIP

The various surface misalignments and protruding structures seen during construction were caused mainly by human error. The local steel contractor did not follow the construction drawings carefully and improvised as the structure was being built. Moreover, the lack of expertise in welding of workers caused 17 out of 20 welds at critical stressed joints to fail in the structural x-ray test. A rigorous contractor selection process and a systematic monitoring procedure during construction must be mandatory for structural steel constructions. To plan for the worst, procedures for on-site fabrication troubleshooting and ad-hoc assembly customisations should also be planned jointly and agreed upon between the design team and contractors.

6.3. LIMITED TOOLS

Current CAD/CAM tools for scanning and milling may be sufficient for the purposes of this Ganesh fabrication but as statue designs become more complex, new tools that can help generate structural frames and suggest efficient surface milling parts may be a more effective tool in the future. The combination of a six-degree of freedom CNC milling machine and computer-generated moulds would significantly increase the accuracy of this type of fabrication as well.

7. Conclusion and future plans

The construction of the tallest Ganesh statue in Thailand was a great learning experience. Although the actuality of the fabrication and construction process did not align well with the plan, but it did highlight many problems and suggest new ways to build more effectively for future projects. Most importantly, combining the digital model into a shared environment where the team can utilise and refer to, hiring professionals with real expertise in steel fabrication, and employing new CAD/CAM tools to generate more accurate moulds are procedures that should be explored to its fullest potential.

In the future, the lessons learned from this experience will be shared and improved on in the next project, a 40-meter tall bronze Buddha statue in Kanchanaburi province which will break ground on March of 2012.

Acknowledgements

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ORNAMENTAL DISCRETISATION OF FREE-FORM SURFACES

Developing digital tools to integrate design rationalisation with the form finding process

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Abstract. The adoption of digital planning methods has given rise to an unprecedented formal freedom in architectural design. Free-form shapes enjoy considerable popularity in architectural production today. However, these shapes prove to be notoriously hard to fabricate. This paper reports on an ongoing research project investigating the approximation of continuous double-curved surfaces by discrete meshes consisting solely of planar facets, which can be constructed efficiently by using standardised, mass-produced building materials. We introduce our geometrical approach, which is based on the intersection of tangent planes to the surface, and present the digital tools we conceived to integrate the processes of design rationalisation and form-finding.

Keywords. Digital tool-making; parametric design; free-form surfaces; design rationalisation; planar discretisation.

1. Introduction

With Leon Battista Alberti's claim that architecture ought to be separate from construction, a profound change of the profession commenced. Being more and more emancipated from the act of building, architects became to be foremost the authors of planning documents, while the problem of realising their designs became the task of engineers and construction specialists. This division of design and production holds up until this day and, moreover, was reinforced by the emergence of digital planning methods during the past decades.

It's just natural that many architects, as authors of design documents, decided to adopt software programs excelling at the production of representational imagery - software which was originally conceived for computer animation or the automotive and aviation industries. These programs enabled architects to create and manipulate even the most complex of shapes and allowed for an unprecedented formal freedom in architectural design.

The most prominent novelty the digital modelling programs brought with them was the introduction of free-form surfaces to the formal language of architectural design. These surfaces were hard to describe using ruler and compass, but could easily be mastered with the aid of a 3d modelling program. However, the software packages did not come with the functionality it takes to rationalise designs so that the new formal vocabulary could be materialised with reasonable efforts.

Design rationalisation can be defined as "the process of approximating an intended form with a well-defined generative principle in order to facilitate building execution" (Fischer 2007, p. 45). Today this task is often performed by digital production specialists after a design has already been conceived. The fruitful process of trying to bring form, structure and the means of their production into the best possible accordance cannot happen in this division of labour.

In this paper we introduce a method to transform continuous double-curved surfaces into discrete meshes consisting solely of planar facets and present the digital tools we conceived to integrate the processes of design rationalisation and form-finding.

2. Discretisation of free-form surfaces

Continuous double-curved shapes have proven to be notoriously hard to fabricate in an architectural scale. Manufacturing free-form building elements usually requires the production of custom moulds for every single building element, which naturally results in high construction costs. For this reason various techniques to adapt the shape of free-form surfaces have been explored to make their construction more efficient (Shelden 2002, Pottmann et al. 2008a, Eigensatz et al. 2010). The approximation of continuous double-curved surfaces by discrete planar meshes has thereby been a topic of great interest, since the fabrication of shapes consisting solely of flat panels is far less costly than the production of curved building elements.

The most straightforward way to transform a continuous surface into flat panels is to approximate the surface with a triangle mesh. This method has been used in a number of outstanding built projects like the Great Court of the British Museum (Norman Foster and Partners with Büro Happold, Figure 1a)

or the Fiero Milano (Studio Fuksas with Schlaich, Bergermann and Partners, Figure 1b).

Any arbitrary surface can be triangulated, but when it comes to production the resulting shape is economically less advantageous than equivalent surface structures consisting of panels with more than three sides (Glymph et al. 2004, Pottmann et al. 2008b). Working on the realisation of Frank Gehry's design for the Museum of Tolerance in Jerusalem, Glymph et al. developed a method to tessellate surfaces into planar quadrilateral facets. Their approach is based on the special geometrical properties of translational surfaces (surfaces that are created by sweeping one curve along another curve) and rotational surfaces (created by revolving a curve around an axis) and thus its application is restricted to these classes of shapes. While the Museum of Tolerance was never realised, the roof of Berlin Zoo's Hippopotamus House (Jörg Gribl with Schlaich Bergermann and Partners, Figure 1c) is a built example of a quadrilateral mesh based on a translational surface.

Liu et al. (2006) later introduced a method to discretise a general double-curved surface by optimising a quad mesh that approximates a double-curved shape so that its faces become planar. Similarly, Wang and Liu (2010) developed an approach based on mesh optimisation to produce hexagonal panelisations.

Figure 1. (a) Great Court of the British Museum, (b) Fiero Milano, (c) Berlin Zoo Hippopotamus House.

Our approach to the discretisation of free-form surfaces is based on the intersection of tangent planes (Cutler and Whiting 2007, Troche 2008, Bagger 2010, Stavric and Wiltsche 2011). We take a number of two-dimensional points that can be arbitrarily distributed and map them onto the [uv]-parameter space of a given non-periodic, double-curved surface. We will call the resulting points on the surface "*pattern points*" since they determine the pattern scheme of the emerging planar facets. To every pattern point we determine its tangent plane T to the given surface and intersect it with the tangent planes of adjacent points. As illustrated in Figure 2 the intersection of T with the tangent planes

of two adjacent pattern points yields a vertex of the polygon that defines the boundary of the facet laying in tangent plane *T*. Because all vertices found by intersecting with *T* necessarily lay in this plane, the resulting polygon boundary is guaranteed to be planar.

- P....Pattern points (base points of tangent planes)
- T....Tangent planes
- V....Vertex of a panel boundary polygon

Figure 2. Tangent plane intersection.

Besides generating absolutely planar facets, a mesh produced by the presented method will naturally tend to a configuration where only three panels meet at each vertex. In comparison, an average of six panels meet at the vertices of triangulated meshes, which leads to far more complicated construction details.

Unlike other discretisation techniques, such as triangulation or quad meshing, shapes created with the presented approach can be composed of polygons with varying numbers of sides. Tangent plane intersections produce a complex ornamental pattern, potentially introducing a new expressive quality to a design project. One of the favourable characteristics of this approach is the level of detailed control it offers to designers. The pattern scheme can easily be altered by simply manipulating the pattern points that determine the tangent planes along the surface. The presented method not only allows to control the discretisation process as a whole, but also enables designers to perform selective optimisations to the discrete shape. Pattern points can be moved, added or deleted locally, without changing the overall geometry. This allows the precise control of the emerging discrete shape - of both aesthetic and performative aspects.

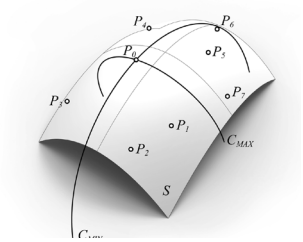
While the calculation of tangent planes to a free-form surface and their intersections is trivial, the challenge is to judge whether two pattern points are adjacent and the intersection of their tangent planes yields a valid edge of a facet boundary polygon. Therefore the interplay of pattern point positions and local surface curvatures must be accounted for.

We have developed an efficient algorithm that solves this problem for surfaces with positive Gaussian curvature and are currently in the process of

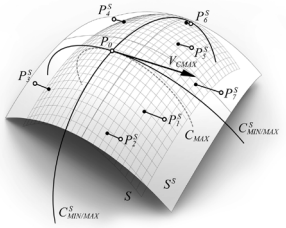
adapting the method so that it will also be possible to discretise surfaces with negative Gaussian curvature using the same strategy.

We begin by performing a Delaunay triangulation of the original two-dimensional pattern points. This initial triangulation gives a first result for the correlation between the given points and is used to determine a set of adjacent candidates for every point. To determine which candidates are truly adjacent to a pattern point, the candidate points have to be projected onto the tangent plane of the pattern point that is investigated. We found that if the minimum and maximum curvatures of the surface at the investigated point are equal (which, for example, is the case at the centre of a paraboloid of revolution), the Delaunay triangulation of the projected candidates in the tangent plane reveals the valid set of adjacent points.

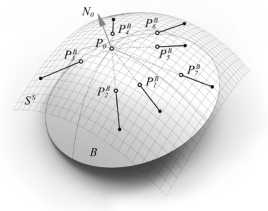
But since surface parts with equal minimum and maximum curvatures are a rare case with free-form shapes, another step is necessary. To compensate for the local surface curvatures, we consider the osculating paraboloid (Pottmann et al. 2007) to the surface S at the investigated point P_0. We calculate the ratio of minimum and maximum surface curvature at P_0 (illustrated as the principal curvature circles C_{MIN} and C_{MAX} in Figure 3b) and scale the candidates according to the square root of this ratio non-uniformly in the direction of the maximum curvature vector V_{CMAX} (Figure 3b). We take the resulting points P_S and project them onto the osculating paraboloid B at P_0 with P_0 as the projection centre (Figure 3c). These transformations compensate the local surface curvature variations around P_0. The resulting points P_B are projected normal onto the tangent plane T in P_0 (Figure 3d). The Delaunay triangulation of the projected points in T (Figure 3d) finally yields the correct correlation between the pattern points: every candidate that is directly connected to P_0 in the triangulation is an adjacent point and its tangent plane must be intersected with the tangent plane of P_0 to get the valid facet laying in the latter plane.



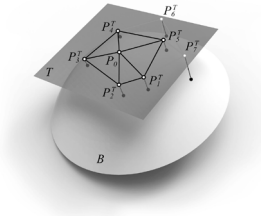
(a) Original pattern points and surface



(b) Scale transformation



(c) Projection onto the osculating paraboloid in P_0



(d) Normal projection onto the tangent plane of P_0 and Delaunay triangulation

Figure 3. Finding the correct set of adjacent points for the tangent plane intersection.

Since thoroughly discussing the geometrical backgrounds of this approach is out of the scope of this paper, I would like to refer the reader to Stavric and Wiltsche (2011), where the geometry of the presented method is discussed in much greater detail.

The described process of compensating local surface curvatures has to be repeated for every pattern point. Although this might sound like a time-consuming task, the computations are straightforward. To give a few numbers, the discretisation of a surface consisting of 1000 facets currently takes about 70 milliseconds on a PC equipped with a 3.4 Ghz i-7 quadcore processor. This gave us the opportunity to develop design tools that provide immediate feedback to the actions of a designer, which we deem as an essential feature of our work.

3. The Tools

In the course of our research we have developed a set of digital tools to integrate the presented approach of free-form surface rationalisation into the design process form early design stages on.

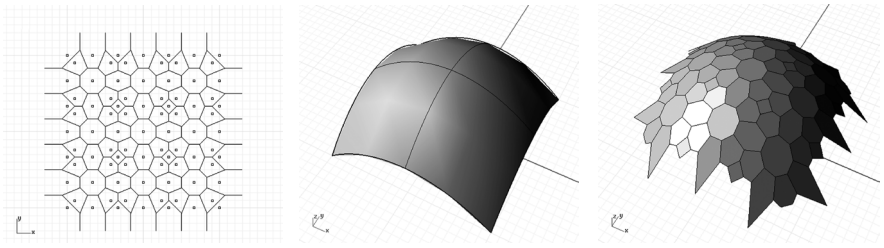
The implementation of our tool kit can be divided into two components: the core algorithm (the encoded geometrical and mathematical knowledge to perform the discretisation of a given surface) and the interface provided to

control and refine the panelisation process (the actual tools to be used by the designer). We decided to prototypically implement our tools for McNeel's Rhinoceros Software since "Rhino" is excellent with modelling free-form surfaces and enjoys considerable popularity in the architectural community today. Furthermore, due to the common ground of software development for Rhino and its parametric modelling extension, Grasshopper, we were able to efficiently develop explicit modelling tools for the direct manipulation of geometries, as well as a pure parametric modelling interface to our algorithms - both enabling an inherently different workflow.

4. Direct modelling interface

The central element of our direct modelling interface is the "*discrete surface*" - a new constraint-based geometrical object type we introduce to the modelling environment, complementing Rhino's native NURBS surface and polygon mesh objects. The discrete surface is not just a descriptive geometrical object but an active representation that reacts to modifications performed by the designer, automatically forming the panelised approximation of a continuous surface using a given pattern scheme.

To create a discrete surface the designer has to define an initial pattern scheme as a set of planar points as well as a double-curved surface to discretise. The pattern scheme points in Figure 4a were created using a small tool we made for the quick generation of panelisation patterns. As depicted, the tool also displays the Voronoi diagram for the generated set of points. Although the emerging panel scheme of the discrete surface deviates from this diagram, it generally gives a good idea what to expect on a surface with positive Gaussian curvature.



(a) Initial pattern scheme *(b) Continuous surface* *(c) Generated discrete surface*

Figure 4. Creating a discrete surface.

Once created, the discrete surface can be refined by simply moving the pattern points along the surface (Figure 5) and by adding new points or removing exist-

ing ones. Manipulating pattern points works just like transforming any other points in Rhino, with the exception that they are constrained to move along the surface. While editing the discrete surface, designers can take advantage of the full range of geometrical modelling aids Rhino offers (simultaneous transformation of multiple objects, object snaps, construction grid, etc.).

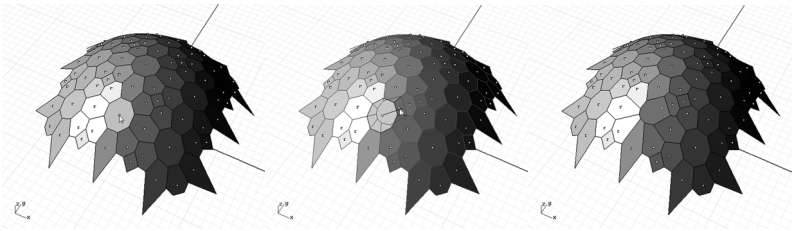


Figure 5. Editing the panelisation scheme by moving pattern points along the surface.

As illustrated in Figure 6, the shape of the original continuous surface can still be transformed by editing the control points of the surface subobject.

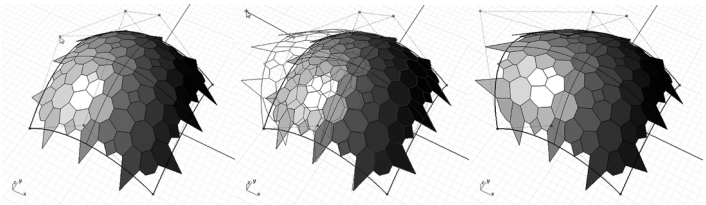


Figure 6. Changing the shape of the continuous surface subobject by editing its control points.

Due to the short computation times of the discretisation algorithm, changes to the surface shape and pattern scheme are reflected in real time, which gives designers immediate feedback on their actions - even when working on a shape consisting of thousands of panels. By providing an active geometrical representation of a discrete surface which allows the interactive refinement of designs, we aim to facilitate an explorative design approach and the continual "talk-back" (Schön 1983) with the design problem. However, relying solely on geometrical constraints is not sufficient in many cases. Therefore we extend our tool kit to Rhino's parametric design environment, Grasshopper. Offering a parametric interface to our algorithm, we enable designers to include their own project specific constraints and to potentially enhance their design approach.

5. Parametric interface

Although the direct manipulation of geometries using explicit modelling tools is generally perceived to be the most intuitive way of designing with digital tools, algorithmic form-finding techniques are employed by a growing number of digitally advanced practitioners. These techniques require that a design is described by a parametric model instead of a concrete geometric representation. The parametric model thereby describes the process how to arrive at a certain form rather than the form itself.

Additionally to the direct modelling interface we created a Grasshopper component that provides a parametric interface to our algorithm. The component can take either geometrically defined or parametrically generated surfaces and pattern point sets as inputs, it outputs the generated discrete mesh geometry which can then be further processed inside Grasshopper.

Figure 7 shows a fully parametric 3d model of a prototype design to be constructed later this year. The structure will be fabricated from cross-laminated timber (CLT) panels and features a custom joint system which was developed for this self-supporting prototype structure (Schimek et al. 2010). The panel geometry, the joints and slots were generated parametrically, based on the output of our Grasshopper component.

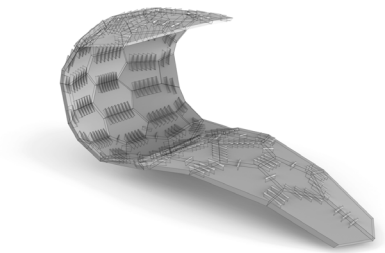


Figure 7. Parametric model of a prototype structure.

6. Outlook

Our future work will focus on three topics. As already mentioned we are currently in the process of adapting our geometrical approach so that it will also be possible to discretise surfaces with negative Gaussian curvature using the same strategy. Our second line of research focuses on the construction of the self-supporting prototype structure mentioned before. We are currently extending our set of tools to incorporate design constraints tailored for this construction strategy. And finally, we are working on the automated generation of data to drive the digital production of panels using computer numerically controlled mills. This will complement our tool kit to form a complete digital chain

for the construction of discrete surfaces, reaching from early design stages on through to the fabrication process.

Acknowledgements

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3D URBAN SPACE INFORMATION SYSTEM

A preliminary prototype based on Google Earth Plugin

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Abstract. 2D GIS has shown its limitations in many situations, especially when it's applied in urban design. Many studies have been carried out to deal with the problem. Some attempted to link 3D visualisation to data stored within 2D GIS, and others tried to combine GIS, CAD and visualisation together. They all aim to meliorate current GIS for 3D applications. The authors of this paper developed a preliminary prototype of a 3D urban space information system based on Google Earth Plugin. It sets up a server to store and offer specific urban space information. With the desktop application that embeds Google Earth Plugin, user can upload and download models on the server, view them in the virtual 3D environment of Google earth, and make models directly in the 3D environment. A server-side database plays the role of managing information. This paper introduces the key ideas and methods of the system development, including system structure, set-up of the serve, server side information management, and interactive modelling functions.

Keywords. GIS; urban design; Google Earth plugin; VB.Net.

1. Introduction

Urban space information is crucial for urban planning, design and management. Since the early 1990s GIS has become a sophisticated system for maintaining and analysing spatial and semantic information on spatial objects (Stoter and Zlatanova 2003). In urban planning, desktop GIS packages such as ArcView and MapInfo have become standard and near routine (Batty et al. 1999). Existing GIS packages are widely used for handling, storing, manipulating and ana-

lysing 2D spatial data (Rahman et al. 2001). Urban space information handled with such GIS packages are usually differentiated into geomorphic information such as buildings, roads, and green lands, administrative division information such as borders of cities and districts, and the attribute information of the above, and the former two are usually in the forms of digital line graphic, digital orthophoto map, digital terrain model or digital raster graphic.

2D GIS has shown its limitations in many situations, especially when applied in urban design, which has been defined as "...the process of giving physical design direction to urban growth, conservation and change" (Barnett 1982, p.12). Urban designers often deal with large volumes of urban information, thus GIS is appropriate for this purpose. However, they need 3D environment to support design, and they usually utilise 3D design software on a CAD basis to communicate their vision (Rode 2006). Urban design sits astride the world of 2D and the world of 3D as yet there are but the most tentative links between desktop GIS and CAD (Batty et al. 1999).

There are many studies carried out to deal with the problem. Some researches attempted to link 3D visualisation to data stored within 2D GIS. Around the middle of the 1990s the UCLA group pioneered the delivery of geographic information into a 3D modelling environment (see Batty et al. 1999). Later studies include the work by CASA on the integration of GIS data into cityscape presentations of the City of London (Dodge et al. 1997, Batty et al. 1999), the VRML-based interface to GIS called GOOVI-3D developed by Fraunhofer Institute of Computer Graphics in Germany (Coors and Jung 1998), GeoVR system developed by the University of Hong Kong (Huang and Lin 2002), the Sheffield Urban Contextual Databank from the University of Sheffield (Peng 2003), and the research work from Old Dominion University and Southwest Jiaotong University of Chengdu in China (Zhou et al. 2006). Some researches attempted to combine GIS, CAD and visualisation together, such as KARMA-IV developed by the Delft University of Technology in the Netherlands (Verbree et al. 1999) and CommunityViz by the Orton Family Foundation (ESRI 2001). Most of the studies applied virtual environment technology especially VRML models for 3D visualisation, enabling various people access easily via internet and thus share the information. General speaking, the studies still aim to meliorate current GIS for 3D applications.

In this paper, we will present a 3D urban space information system based on Google Earth Plugin, which could be a supportive platform for urban design and management. Google Earth, as a free platform of virtual globe, map and geographical information, provides a real-time virtual 3D world that people can see satellite images of the Earth's surface, 3D terrain, 3D buildings, and so forth at any angle. People can also add and manage their own

geospatial data such as raster images and 3D models of buildings and structures in the 3D world based on Keyhole Markup Language (KML) (Google Earth 2012). It supports normal GIS data forms and, more importantly, 3D models, making it possible to build up an urban space information system based on it. Our system is a client-server structure, using SQL Server as data management system. We used Visual Studio as the programming platform, embedding Google Earth Plugin API in VB.Net application. With our system, normal users can load server-side or client-side urban models to the Google Earth Plugin environment, and make simple models of buildings, roads, and plot borders directly in the environment. The high-level users can upload or erase models on the server to update the urban environment.

2. System structure

Figure 1 shows the system framework. Google serve offers the general information of urban terrain, the urban space information server stores the 3D models of urban space in KML/KMZ format, and the client program, with the embedded Google Earth Plugin API, can upload/download the data from Google serve and the urban space information server, and presents them on Google earth. The client program also offers some 3D modeling function to support simple urban design.

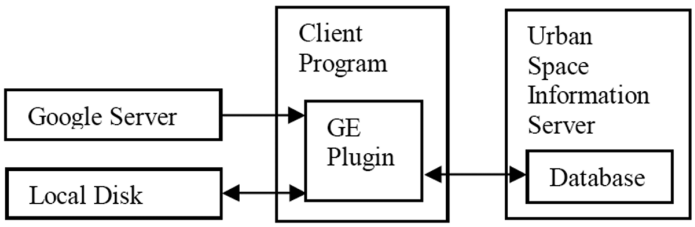

Figure 1. System structure.

3. Set-up of urban space information server

We set up IIS for uploading and downloading files on the urban space information server. The KML/KMZ-format model files of urban space elements are stored in a specific folder. To escape duplication, names of the uploaded files are renamed automatically, each consisting of system time and four random numbers. This is controlled by defining a custom UploadHandler Class on the server. In order to upload files larger than 2M, some modification is made to the Web.config file. For querying and managing the models, SQL Server is installed as well.

Non-graphic information is stored in the following tables in the database: (1) Plot Information Table, including plot number, plot name, and remark, (2) Category Information Table, including category number, category name and remark (Category refers to different kind of urban space element, such as building, road, and plot border) and (3) Urban Geo-data Table, to store the description information about each file of urban space element, including number, title, the plot that the element is on, the category that it belongs to, creator, creation time, file name, and remark.

When users modify any information, corresponding record will be added, deleted or modified in corresponding table. We assumed three kinds of users: (1) normal users, who can query, download files on the server and load or unload models in the Google Earth Plugin environment; (2) administration users, who additionally can upload and delete files on the server to update the urban information; and (3) the super user, who can edit data in Plot Information Table and those in Category Information Table, as well as manage other users. Corresponding tables are designed to store users' information in the database.

4. Development of client program

The client program mainly consists of five modules: (1) urban space view control, (2) interactive modelling, (3) client-side urban space information management, (4) server-side urban space information management, and (5) database management. The program was developed with VB.Net. When user runs the program, the interface of the program as Figure 2 shows will present after login in. (The two right-bottom buttons referring to database management only show to the super user).

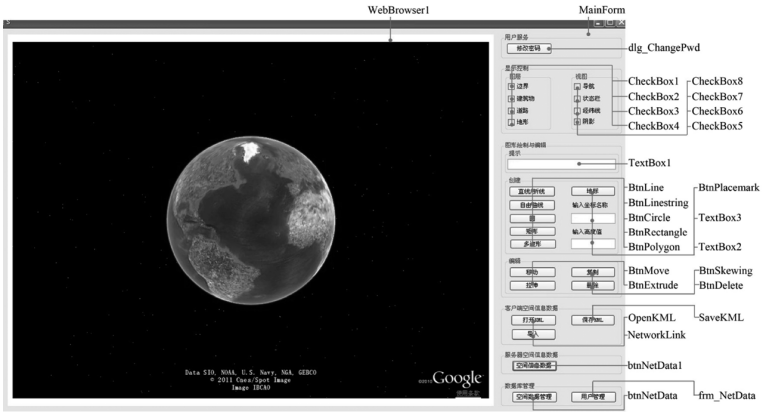

Figure 2. The interface of the client program.

4.1. EMBEDDING GOOGLE EARTH PLUGIN IN VB.NET

Google Earth Plugin and its JavaScript API allow users to place Google Earth instance into web pages, after installing the plug-in program offered by Google. While they are designed for JavaScript programming for web applications, the plug-in can be embedded in desktop applications and the API can be accessed via other programming platforms (Chapman and Nurik 2010). To embed Google Earth Plugin in our VB.Net application, we include GEPlugin Type Library, place a WebBrowser in the main form, and browser a certain web page on the urban space information server when the main form is loaded. The exemplar of the web page is introduced by "Google Earth API Developer's Guide" (2010). Its core function is *init*. When succeed, *initCB* is called to show the Google Earth instance and get the handle of it. The following is the codes of the two functions.

```
function init() { google.earth.createInstance('map3d', initCB, failureCB); }
function initCB(instance) { ge = instance; ge.getWindow().
setVisibility(true); }
```

In order to use the functions in GEPlugin Type Library to access the Google Earth Plugin instance in our programming, we add another line as *window.extenal.JSInitSuccessCallback(ge)* in the *initCB* function to call a subprogram in the VB.Net codes to transfer the handle to VB.Net. The codes of JSInitSuccessCallback are the following:

```
Public Sub JSInitSuccessCallback_(ByRef pluginInstance As Object)
    m_ge = pluginInstance
End Sub
```

Thus and through establishing a trust relationship between VB.Net and JavaScript, the Google Earth Plugin instance can be accessed by VB.Net through *m_ge*.

4.2. SERVER SIDE URBAN SPACE INFORMATION MANAGEMENT

When the button "btnNetData1" (see Figure 2) is pressed, the dialogue as Figure 3 shows presents to enable user to manage the information on the server. The user can query files, upload files, download, delete, edit the attributes of the selected elements, or load, unload the selected models on the Google Earth instance. The above frequently used SQL functions are encapsulated in DbHelperSQL Class. Through comparing query criteria with the records in the database, the query result will list out. If the "cbIsLoad" is checked, the rows of the models already loaded on the Google Earth instance are marked in red.

The way to find out the loaded models is traversing all the items of Google Earth instance's KmlFeature object: if the type of an item is *NetWorkLink* and the *url* of the network link is equal to a result of the query, the corresponding line will be marked.

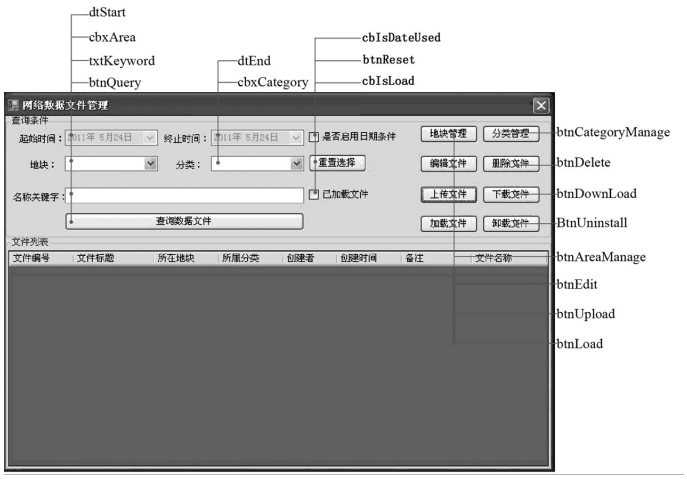

Figure 3. The interface for managing the urban space information on the server.

The user may select items in the query result, and then delete them, load or unload them on the Google Earth instance, or edit one item's attributes in the database. To load or unload the models on the Google Earth instance, the program will use the same process above to check whether the models are already loaded, and then call the API's getFeatures.appendChild function or getFeatures.removeChild function.

Figure 4. The dialogue for editing item's attributes.

Figure 5. The dialogue for inputting item's attributes.

To edit the attributes of a selected item, the program will open the dialogue as Figure 4 shows. The program then changes the corresponding record in the database. To delete selected items, the program simply deletes the corresponding records in the database, and erases the corresponding files on the server.

Pressing the "btnUpload" button in Figure 3, the user can upload KML/KMZ file to the Server. After filling the attributes in Figure 5, the program will add a record in the database, rename and upload the file to the server.

Figure 6 shows the interfaces for the super user to edit the information in Plot Information Table and Category Information Table. The program simply responds to the super user's command to add, delete, or modify the records in the database.

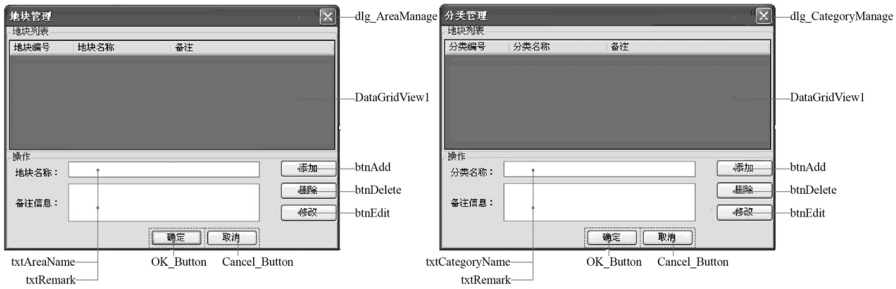

Figure 6. The dialogues for editing Plot Information Table and Category Information Table.

4.3. INTERACTIVE MODELING FUNCTIONS

We had the intention to make our system a platform for urban design, so that some interactive modelling functions are included to provide a tool for studying building volumes in urban space. Google Earth API offers functions to create simple geometry shapes on Google Earth instance and get KML codes of them. In the API, the relationship between various classes prefixed "kml" is actually the same as the structure of KML.

The process of creating a geometry shape is: (1) capturing the mouse events and the coordinates, (2) creating a KmlGeometry object and change its coordinates attribute, (3) creating a KmlPlacemark object and setting its geometry attribute to the above KmlGeometry, and (4) appending the above KmlPlacemark to Google Earth instance's KmlFeature object. The typical codes (not including mouse event capturing) would be the following:

```
linestringPlacemark =AxGEPluginCoClass1.createPlacemark("")
linestring =AxGEPluginCoClass1.createLineString("")
coords = linestring.getCoordinates
```

coords.pushLatLngAlt(lat1, lon1, alt1)
coords.pushLatLngAlt(lat2, lon2, alt2)
linestringPlacemark.setGeometry(linestring)
m_ge.getFeatures().appendChild(linestringPlacemark)

The events that the program captures include eventGEEventEmitter-Mousedown, eventGEEventEmitterMouseup, eventGEEventEmitterMouse-move. Corresponding functions was programmed to capture the mouse button number and the coordinates when the event happens, and save them in globe variables to transfer to the functions of creating geometry shapes.

The process of editing a geometry shape is: (1) interactively selecting a shape, (2) getting the shape's coordinates and other geometric attributes, and (3) changing the coordinates and attributes. If needed, mouse events are captured as well. Figure 7 shows the flow of changing the shape of a polygon.

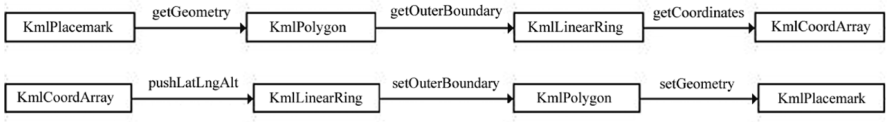

Figure 7. The flow of changing the shape of a polygon.

The created geometry can be saved in local disk with the following process: Getting the KML codes of the geometry with the API's getKML function, then write them to a local file with System.IO's.StreamWriter.Write function.

5. Test use, conclusion and further development

The system was tested with the campus of Nanjing University as experimental sample. A simulative server was set up on local computer. The urban space information elements (models) were created with AutoCAD or SketchUp and transferred to KML or KMZ format. Figure 8 shows the list of all the elements after being uploaded to the server, and Figure 9 shows the 3D view of the campus when all the building models were loaded on the Google Earth instance. Figure 9 shows some screenshots of an interactive modelling process of a building volume study for an assumed project.

What we have developed is just a preliminary prototype. It has explored a possible structure for a 3D urban space information system based on Google Earth Plugin, as well as the preliminary functions. It utilised the advantages of Google Earth such as web-based geo-data sharing, virtual environment of 3D visualisation, and simple 3D modelling capability, combining the ability of database in information management. With current system, user can collabo-

ratively compose and update 3D city models with individual CAD models, flexibly navigate the city models, and carry on study or design of urban space with the city models. The next step will focus on a more realistic data structure, the ability of creating more complex models, friendlier user interfaces, and the ability of managing larger data. The furtherer work of handling, storing, manipulating and analysing various unban space information is to be carried out to achieve a comprehensive 3D urban space information system that could be applied in urban planning, design, and management.

文件列表

文件编号	文件标题	所在地块	所属分类	创建者	创建时间	备注	文件名称
35	地质楼	地块1	建筑物	admin	2011-5-1 10:54	标志建筑物	20110501105425...
36	丙丁楼	地块1	建筑物	admin	2011-5-1 10:54		20110501105457...
37	大礼堂	地块1	建筑物	admin	2011-5-1 10:55		20110501105555...
38	地块一边界	地块1	地块边界	admin	2011-5-1 10:56		20110501105655...
39	地质实验楼	地块1	建筑物	admin	2011-5-1 10:57		20110501105722...
40	东北楼	地块1	建筑物	admin	2011-5-1 10:57		20110501105742...
41	东大楼	地块1	建筑物	admin	2011-5-1 10:58		20110501105807...
42	东南楼	地块1	建筑物	admin	2011-5-1 10:58		20110501105823...
43	费鲁民楼	地块1	建筑物	admin	2011-5-1 10:58		20110501105841...
44	汉口路北大门	地块1	建筑物	admin	2011-5-1 10:59		20110501105919...
45	化学楼	地块1	建筑物	admin	2011-5-1 10:59		20110501105954...
46	计算机网络中心	地块1	建筑物	admin	2011-5-1 11:00		20110501110012...
47	甲乙楼	地块1	建筑物	admin	2011-5-1 11:00		20110501110031...
48	教学楼	地块1	建筑物	admin	2011-5-1 11:00		20110501110046...
49	吕志和游泳馆	地块1	建筑物	admin	2011-5-1 11:01		20110501110121...
50	樊民书楼	地块1	建筑物	admin	2011-5-1 11:02		20110501110214...
51	树华楼	地块1	建筑物	admin	2011-5-1 11:02		20110501110235...
52	体育馆	地块1	建筑物	admin	2011-5-1 11:02		20110501110256...
53	田家炳楼	地块1	建筑物	admin	2011-5-1 11:03		20110501110313...
54	图书馆	地块1	建筑物	admin	2011-5-1 11:03		20110501110330...
55	文科楼	地块1	建筑物	admin	2011-5-1 11:03		20110501110353...
56	戊己庚楼	地块1	建筑物	admin	2011-5-1 11:04		20110501110412...
57	西大楼	地块1	建筑物	admin	2011-5-1 11:04		20110501110436...
58	西南楼	地块1	建筑物	admin	2011-5-1 11:04		20110501110455...
59	辛壬楼	地块1	建筑物	admin	2011-5-1 11:05		20110501110518...

Figure 8. List of elements.

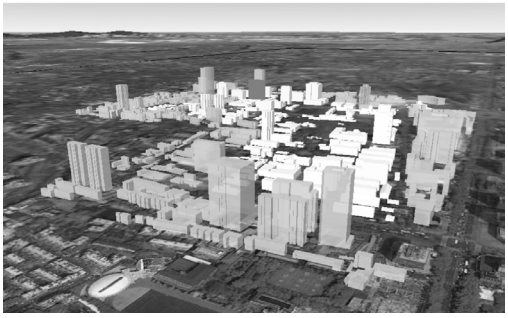

Figure 9. A 3D view of a test run.

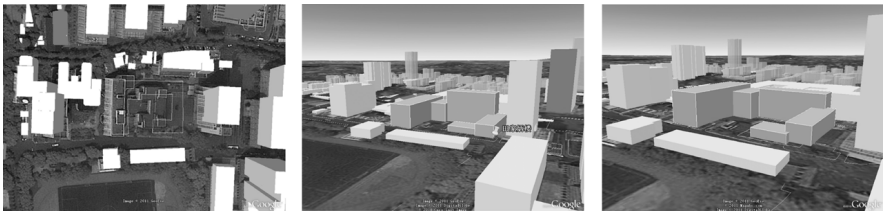

Figure 10. Screenshots of an interactive modeling process.

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Verbree, E., Maren, G., Germs, R., Jansen, F. and Kraak, M. J.: 1999, Interaction in virtual world views: linking 3D GIS with VR. *International Journal of Geographical Information Science*, **13**(4), 385–396.

Zhou, G., Tan, Z., Cen, M. and Li, C.: 2006, Customizing visualization in three-dimensional urban GIS via web-based interaction, *ACSE Journal of Urban Planning and Development*, **132**, 97.

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COMPUTER SIMULATION FOR INTUITIVE STRUCTURING

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Abstract. Computer simulation methods have opened up new possibilities for design and research by introducing environments in which we can manipulate and observe. For instance, architects utilise three-dimensional modelling tools to simulate architectural geometries, and engineers use Finite Element software to simulate structural behaviour. Simulation tools make certain aspects of architecture efficient, but, on the other hand, they have brought new types of challenges into the field. One such challenge is the structuring of so-called complex geometries. These forms are often conceived in an environment where gravity, scales, and material are absent and calculated in a model where geometries are frozen and static. As a result, there exists little understanding between the two disciplines in solving the design to come to a well-negotiated form. In the context thereof, our work focuses on the development of interactive simulation environments that induce intuition towards the specific counter-intuitive problem of structuring in the early stages of design. The paper gives insights into aspects of simulation relevant to architectural design and structural engineering. Subsequently, three simulation environments that we have developed are presented to demonstrate our strategies.

Keywords. Computer simulation; finite element analysis; interactive software.

1. Introduction

Computer simulation and visualisation methods have transformed the ways we comprehend the world as well as how various professions operate today (Turkle 2009). For instance, architects utilise three-dimensional modelling tools to simulate architectural geometries and engineers use Finite Element

software to simulate structural behaviour. Simulation tools enhance the efficiency of certain aspects of architectural practice, but, on the other hand, they have brought new types of challenges into the field. One such example is the structuring of so-called complex geometries.

The connection between form and its structural and material considerations has been an integral part of architecture since its beginnings. However, after the academic separation of the two disciplines was formalised in the 1740s, the distance between the two has been increasing steadily despite attempts to (re)unite the two (Holgate 1986). This has become increasingly apparent and problematic due to the introduction of geometries conceived in a computer environment where gravity and material are absent and scale is vague, calculated in a model where geometries are frozen and static. In other words, each discipline is operating within its theoretical and methodological belief system, which determines how it identifies and solves problems that are reflected and reinforced by the simulation tools.

In the context thereof, our work focuses on the development of an interactive simulation environment that induces an intuitive understanding towards the specific counter-intuitive problem of structuring in the early stages of design.

2. Computer simulation in architecture and engineering

2.1. CURRENT USE OF SIMULATION

Since the construction of the first general purpose computer in the mid-1940s and the development of high-level programming languages in the mid-1960s, computer simulation has become accepted as a powerful approach and an important area of study (Goldsman et al. 2010). The introduction of computer graphics has been particularly important for the emergence of computational perspectives in the field of architecture, which has developed into Computer Aided Design, following the development of finite element analysis (FEA) methods and other engineering tools. A wide range of simulation tools are available today in the domains of idea exploration, risk assessment, information management, and problem solving. In the field of architecture, the focus of modelling and simulation has been on geometric aspects. This is partly due to the proliferation of digital design tools that enable architects to create complex forms that were formerly difficult to manipulate with previous design technologies. At the same time, other simulation tools, such as FEA in structural engineering, have enabled us to assess the constructability of such geometries, and these have been expanding the boundaries of what is possible today in the construction industry.

However, at the same time, we can observe various challenges in effectively controlling the design using simulation tools. For example, architects utilise three-dimensional modelling tools to create a complex geometric form with very little understanding towards its structural behaviour. Subsequently, structural engineers, with the aid of FEA, try to fit and support this predetermined 'ideal' form with more or less homogeneous elements such as beams and columns with very little understanding of its geometric flexibility based the design intentions of the architect. As a result, both parties are required to go through a tremendous amount of trial and error, often resulting in an enormous waste of time and material. Therefore, it seems important to find ways to facilitate understanding between both sets of professionals, particularly with regard to the simulation tools we use today.

2.2. MODELLING AND SIMULATION

Computer simulation involves the modelling of a reality of something, as an abstraction, to facilitate understanding towards a specific aspect of interest. Simulation is a manipulation of a model that enables us to perceive interactions, the relationship between parts, as well as its overall implications, all of which would be difficult to observe otherwise. Generally, it is necessary to iterate the cycle of modelling, simulation, and evaluation to develop a sufficient degree of understanding toward the specific aspect of interest.

As discussed in the previous section, architects and engineers look into different aspects of reality, thus the models they develop as well as manipulate hold different structures and controls. For instance, an architect might model a column with a given thickness in order to see its impact on the space. In an FEA model, on the other hand, one requires the centre line of a column as a geometric input, and the cross-sectional properties are assigned separately along with its material properties. Therefore, at the current state of the art, the models are not interchangeable and require much pre-processing to convert one type to the other. In addition, architectural software gives detailed control over the geometries, whereas an engineering FEA assigns controls to material properties and boundary conditions such as fixings and loadings.

2.3. MODELLING TECHNIQUES AND SIMULATION EVALUATION

A good model requires a skilled modeller. The quality and usability of the model hugely depends on his/her practical experience and level of understanding of the subject. Similarly, enormous domain knowledge is required in order to comprehend and evaluate the simulation results.

A way of overcoming the disparity between the simulation tools, naturally, is to build an environment where both geometric and structural simulations co-

exist. Major commercial software tools used in architecture, such as CATIA, Solid Works, AutoCad Revit, and MicroStation all have structural modules to perform FEA which can be attached to the geometric environment. However, such modules are generally not used by architects but rather engineers, as it is difficult to use them without the relevant experience and knowledge. In addition, the resultant visualisation of the FEA is often insufficient for an architect to make design decisions based on the structural behaviour.

In this context, our belief is that it would be tremendously helpful to develop simplified yet intelligent geometric and structural simulation tools that focus on inducing the intuitive connection between the geometries and their structural behaviour. The following discussions focus on the early stages of architectural design where structural behaviour is particularly opaque to architects. This is because, in many cases, it is difficult to think of structure without a definite geometry. In addition, most of the critical decisions, including the general shape of the buildings, are made during this stage.

2.4. INTUITIVE SIMULATION FOR DESIGN CREATION

Here, we consider intuition as insight gained by practice (input) and feedback (output) which allows one to make informed decisions in the context of a specific design problem.

As discussed, in the particular case here, the aim is to connect geometry and its structural behaviour in a single simulation environment that would aid the making of design decisions in the early stages of design. Computer simulation is numerical and logical in its nature, which is suitable in expressing engineering problems. On the other hand, architectural design problems, for example, are notably ill-defined in their inception; a designer cannot describe the logical steps that led to a goal or even clear evaluation criteria (Simon 1973, Chan 1990). In fact, the development of a design problem itself is an important aspect of design that involves ‘a series of additions and subtractions, decision and changes-of-mind, continuations and reversals’ (Moira 2010). In the early stages of design, architects use modelling tools mainly as a replacement for sketching to generate their design ideas. In this process of conceptual sketching, visual representations are fundamental to architectural design. In fact, they are not a mere record of an idea but an active hint for design generation. Designers use visual cues in observing graphical elements that trigger mental images, which in turn may suggest ideas for the current design (Menezes and Lawson 2006). Therefore, in our simulation environment, we make particular effort in (1) simplifying the user input, (2) speeding up the input-output loop, (3) providing compelling visualisation, and (4) presenting a level of flexibility in the simulation results.

3. Simulation for intuitive structuring

In this section, we present three projects in which we attempt to induce the architect's intuition towards the counter-intuitive domain of structuring (Table 1).

TABLE 1. Project strategies

	Input	Output	3D modelling	FEA
TopoStruct	Simplified boundary conditions for FEA	Various visualisation of the optimal material distribution	None	Real-time FEA analysis with a pre-set material property
FoamTower	Assembly of 3D line elements	Animated deflection and stress distribution of the input geometry	Simplified 3D modelling capabilities	Real-time FEA analysis with a pre-set material property and boundary conditions
Shanghai Expo	A set of parameters for geometric control	Potential errors and crashes between the aesthetics and the structural elements	Pre-coded mathematical description of the designed geometry	None

3.1. TOPOSTRUCT – MECHANICAL INTUITION

One of the applications we have developed (Kaijima and Michalatos 2011), TopoStruct, is based on the theory of topology optimisation (Bendsoe and Sigmund 2002). This is a well-documented methodology that produces notionally optimal geometric and material distributions with respect to structural behaviour (Figure 1).

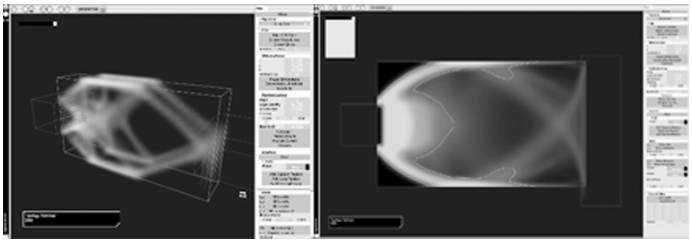

Figure 1. Screen captures of TopoStruct in 3D environment.

TopoStruct was made for exploring lateral structural solutions but also for enhancing a designer's intuition into structural behaviour. In this method a volume of variable density or porosity material is assumed in space and the problem is set up as a set of support conditions and forces acting on this volume. Iteratively the related algorithms attempt to find a topologically optimal solution of material distribution that best meets the given boundary conditions while minimising material use. To enhance the understanding of the structural behaviour of the solution, we offer different ways of visualising the information in 2d and 3d especially the densities, strains and principal stress directions whose patterns can give an idea to the designer about the internal forces that arise in volumes of materials and most importantly the tension and compression regions (Figure 2).

The software has allowed people with little prior knowledge of engineering to acquire an induced understanding of mechanics of material. In fact, after spending some time "playing" with hypothetical scenarios and observing TopoStruct, users tended to anticipate the results, as though they had gained an intuitive understanding of the underlying principle.

Topology optimisation often converges to a familiar solution such as a truss. While we are accustomed to considering trusses as made of nodes and struts, our work offers a glimpse into the abstract concept of a truss as a product derived via a process of continuous distribution of material in space. This reintroduction of a conventional concept as simple as a truss is extremely profound: it is an intellectual emancipation, a deeper recognition that the objects of our world are not given, but shaped to reflect our understanding of its principles.

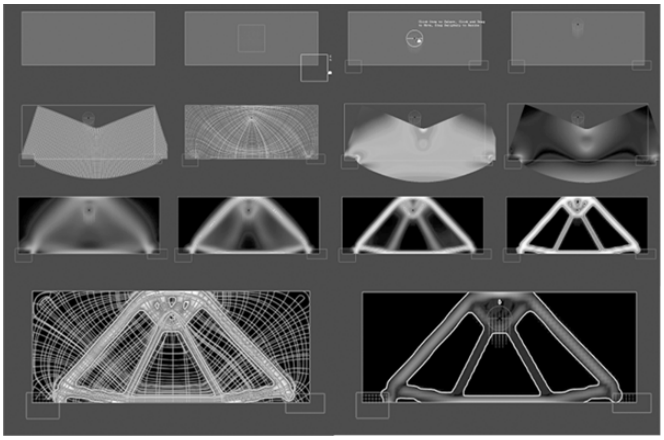

Figure 2. TopoStruct 2D work flow and various visualisation options.

3.2. FOAMTOWER – SYNTHETIC INTUITION

The FoamTower software was developed for a two-hour workshop conducted during an open house event at the Singapore University of Technology and Design by the members of International Design Centre; a research institution within the university. The aim of the workshop was to introduce architectural and engineering design concepts to prospective students through a collaborative learning and building experience of a large-scale design prototype. Participants with no architectural or structural engineering background were divided into a five-to-eight person team and were instructed to design and build the tallest and most unique tower within given constraints. The constraints involved budget, time, material, footprint, and visual appearance. For the construction setup, we used extruded polystyrene (XPS) foam material for the beams, and we devised a joint system using pet-bottles and plastic balls commonly used in the sport floorball, resulting in a joint that is not rigid yet easy to assemble using heat guns and zip ties.

The FoamTower software used in the workshop was developed as an interactive educational tool where geometric, structural, financial, and resource simulations are integrated into one. The interface was designed for team members to quickly learn simple three-dimensional drawing and perform real-time finite element analyses to observe the structural behaviour as well as resource consumption. In addition, the tool allows for a quick stability test with extra loading on the joints to account for the physical properties of the joint system and to provide construction information, such as a list of beam lengths, to ease the building process (Figure 3).

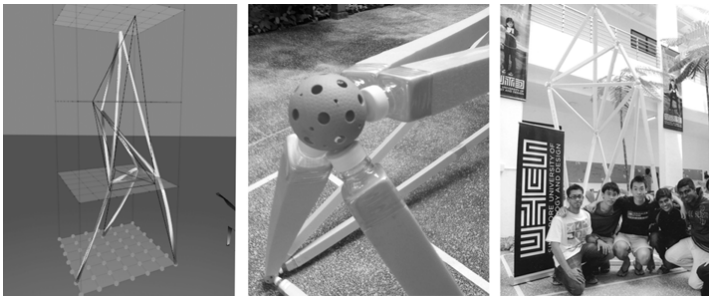

Figure 3. Left: Screen capture of the FoamTower software
Middle: joint system Right: a tower designed and built by the students.

Over the course of three days, we ran a total of five workshops comprising more than twenty-five design teams, where each team came up with a unique solution within the given constraints. It is notable that all teams were able to navigate

themselves through the intricate and interrelated constraints, which would have been difficult to process or track without the aid of the simulation environment. In other words, the constraint boundaries were not only expressed within the software but were present also in the minds of the participants. They developed a dynamic mental image of the problem-solution space where the design process of the tower was a balancing of considerations rather than a representation of an imaginable form. Most of the participants were pleasantly surprised by the outcome they arrived at and expressed that they would not have thought of the solution prior to interacting with the simulation environment. The multitude of tower solutions that were able to satisfy all the constraints is proof of the creative and innovative potential held by this approach.

3.3. SHANGHAI EXPO BRITISH PAVILION—COLLABORATIVE INTUITION

The Shanghai Expo British Pavilion is a project designed by Heatherwick Studio and structured by the firm Adams Kara Taylor (Figure 4). For the project, as a part of AKT team, we designed an interface for the early stages of design where we could observe and discuss the properties and problems of different distribution methods for the 7.5-m long rods both seen as individual elements and as a continuum with statistical and smoothly-varying aspects. This ability to operate intuitively at the crossroads of the discrete and the continuum is critical for projects that are geometrically hyper-fragmented and work in multiple scales.

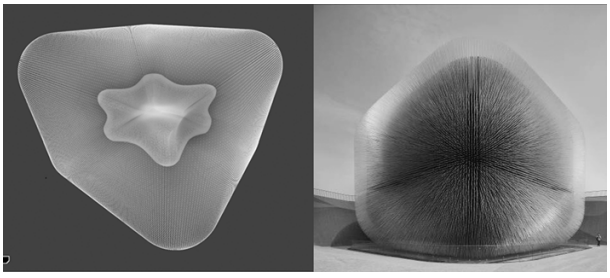

Figure 4. Left: Screen capture of the bespoke software. Right: Shanghai Expo British Pavilion. ©Hufton+Crow.

The pavilion is composed of 60,000 slender rods made of transparent polycarbonate material which perforates each side of the structural box of approximately 10 m × 10 m × 10 m. The unique interior of the pavilion is formed by the end points of these equal-length rods smoothly distributed on a filleted offset of the cube. Achieving such a configuration means that, apart from tweaking the distribution of the outer end points of the rods, one can only

alter the angles at which they penetrate the box. Depending on the projection method of the outer points to the interior, different distributions arise inside the box with varied implied surfaces. From a computational point of view, the initial problem is that of creating a parametric model that is able to handle this number of components and asses in real time the implications of how different decisions affect various problems. In the process, we identified and communicated to the team that a satisfactory distribution of interior rod ends will generate clashes with the structural grid on the box, especially in proximity to the corners. An intuitive understanding of the potential problem and an understanding of the rod distribution logic helped the architects to develop a solution that negotiates between their design objective and the positioning of the structure (Figure 5). At the same time, the engineering side was able to develop a subtle solution to accommodate the remaining clashes by applying a simple curvature to the structural ribs.

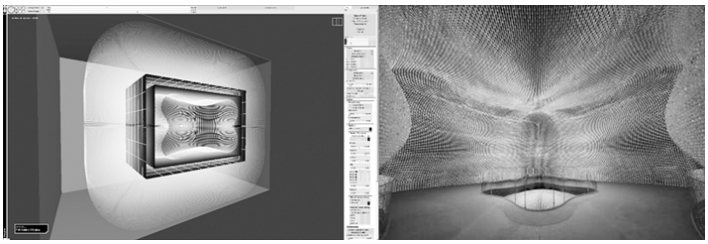

Figure 5. Left: Sections and spike projection studies using bespoke interactive software. Right: Interior-photos of Shanghai Expo British Pavilion. ©Hufton+Crow.

The tools were designed so that they would not necessarily yield a singular optimal solution but would allow the team to interactively develop their intuition into specific design problems in relation to questions of structural efficiency and expressiveness.

4. Conclusion

The paper gives an overview and insights into aspects involved in utilising computer simulation both in architectural design and structural engineering. First, we discuss the consequences we can observe in using simulation tools and then we identify key factors that would help create a better connection and understanding between geometry and its structural behaviour by using the simulation itself. Three simulation environments are presented to illustrate our strategies.

While this instance specifically focuses on the relationship between architecture and structural engineering, similar lines of thought can be applied to

other areas of architecture such as wind, thermal, and acoustic considerations, that are often counterintuitive to architects.

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FINDING VITAL INFORMATION ON HOUSES USING IMMERSIVE MULTI-TOUCH INTERFACE

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Abstract. This paper discusses the creation of natural behaviours for multi-touch house information (MTHI) system using Frustrated Total Internal Reflection (FTIR) technology. After analysing how APPLE and Microsoft defined their touch behaviours we discovered that not enough were responding of commercial application. Therefore using basic touching functions as reference we developed some new gestures and GUI for the real estate market. This system was launched to assist real estate salesmen in Taiwan.

Keywords. House information; navigation; multi-touch; user interface.

1. Introduction

When iPhone and Windows 7 systems were launched between 2007 and 2009, multi-touch and seamless interfaces started to emerge on the market to be tested by common users, changing their perception of the information and how they could manipulate interfaces to access it. Because the project was no longer a laboratory project and started to have a huge influence on people's daily life, The experience acquired in real world design and its immediate impacts are an interesting topic develop, especially when consider a large-scale visualisation with embodied interactions. On the other hand, with the last economic boom, the real estate accumulated huge of information hard to search when using traditional WIMP interface.

How to develop the natural exploration of multi-touch system into the real world design practice is the key of this paper. We were contracted by one of the largest real estate companies in Taiwan to answer their real needs by build-

ing a new system.

We started reviewing the existing house information systems that were not suiting the new multi-touch screen trend and couldn't provide enough immersive user experience. Therefore we started by analysing the information and its classification to redefine the searching gestures on the touch system matching the need for the information visualisation. We created a Multi-Touch House Information (MTHI) system, allowing the users to easily find easily their target houses.

2. Related works

Most of the information on commercial promotion of house is based on DMs, videos, websites, etc. It shows that people are used to "windows, icons, menus and pointers" (WIMP) as you can find on graphic user interface (GUI). But when the environment navigation GUI evolved first from a 2D floor plan to a 360 degree Quick time VR and then immersive seamless environments (Ishida 2002). The input device itself improved first from a keyboard/mouse to a new device with 6 degree of freedom manipulation (Lu 2004) and then to a multi-touch screen (Han 2005). Thus single user navigation status moved to collaboration design status and then to the multi-users status by touching signals input (Naef and Ferranti 2011). The natural user interface (NUI) interaction became the more important topic in the design process and the house information navigation system (Chen and Schnabel 2011).

Therefore we reviewed new touching technologies such as the IR LEDs Metris detection, the 3M company's capacitive method, the optical multi-touch sensing by Han's work (Han 2006), etc. We intended to develop a multi-touch system permitting more than one user searching at the same time by using customised operation gestures for houses navigation. For this reason we chose the FTIR technology for our MTHI system.

An NUI interaction we based on users' behaviours was a kind of experimental transformation of real world activities into virtual simulation. (Lu and Chang 2005). The virtual environments had to be designed to handle a dynamic display of design data using the transparency of the virtual layers creating a clear visual effect easy to follow, for the users (Hirschberg 2003). The navigator widgets are displaying the various options to switch the different operation status (Lepinski et al. 2010).

3. Hardware setup

The hardware structure of the MTHI system is illustrated in Figure 1. For the technology based on the FTIR method, we combine two systems to enlarge

the size of a 4 m × 2.5m (190") touch screen (Figure 1). For the display we use two SXGA+ projectors and the "TV one" video conversion system to merge the graphic interface. The final image resolution is 2050 × 1050 pixels, and we use mirrors to cut by 1/2 the projection distance originally needed. For the touching function, the glasses surfaces are illuminated by 8 IR lasers, using a IR camera and Touchlib to capture the finger points signal (Figure 2).

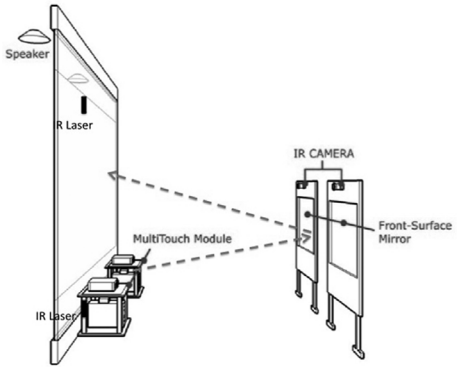


Figure 1. The 190" multi-touch prototype-MTHI.

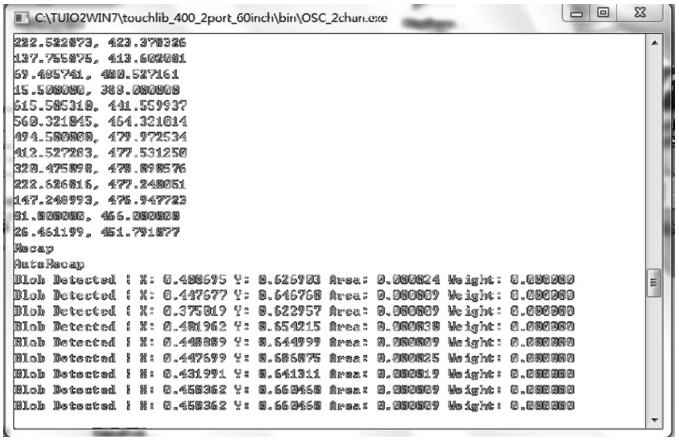


Figure 2. Touchlib detected finger point of X, Y, area, and weight signals.

4. A houses information system

A Multi-touch houses information (MTHI) system is described in a map presentation mode creating an intelligent space designed to carry the real estate company's exclusive luxurious services to its customers. The real estate company data structure is shown in the Figure 3. The customers look for

future investment target Houses in front of a 4 m × 2.5 m screen using three different functions: 1. i-Navigator, 2. The thematic multi-layer, 3. The media info window on the MTHI system.

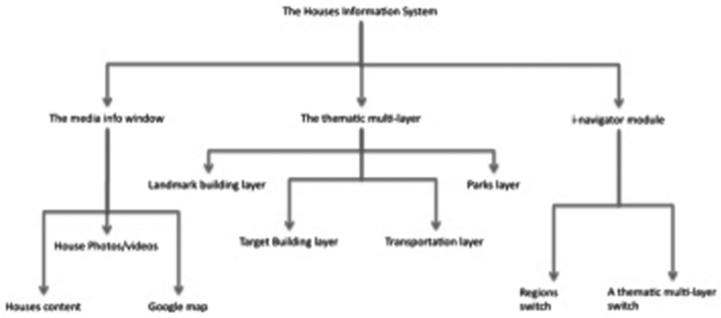


Figure 3. The houses information system architecture.

4.1. I-NAVIGATOR

A navigation wheel flies to wherever the user double-clicks on the sides of the screen. This navigator wheel is like a marking menu that contains switching functions for regions and the thematic multi-layer. "The region switch" can change different area maps from region 1 ~ region n to present a location introduction. "The thematic multi-layer switch" can link different topic layers to show an urban plan in details, from surrounding environments to transportation, etc. (Figure 4). Otherwise, when the user wants to close the text index of the navigation wheel, he only needs to apply two fingers (thumb and index) on it and close the distance between them, to open the text index he just has to reverse the gesture.

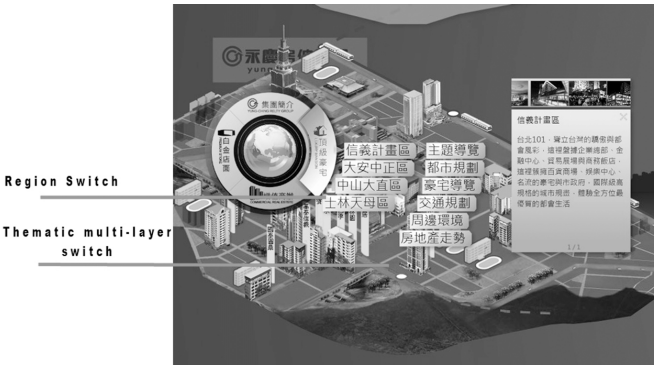


Figure 4. i-navigator to control a present.

4.2. THE THEMATIC MULTI-LAYER

The thematic multi-layer drags different theme layers (e.g. urban plan, transportation, landmark buildings, target buildings and parks) going from top to bottom, to explain the value of luxury residential properties. By touching the main map of the thematic multi-layer the users can pull out a map on the topic they chose. Then the different topic layers will separate with different topic info (Figure 5).

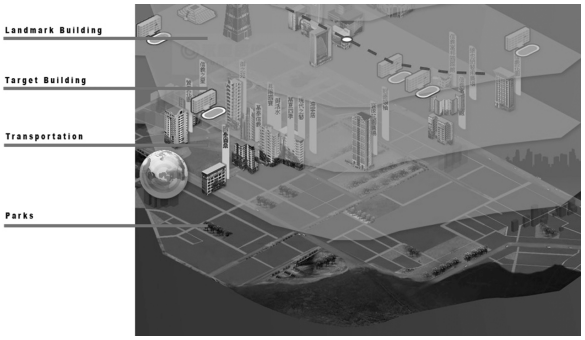


Figure 5. There are different topic layers to describe value of the land.

4.3. THE MEDIA INFO WINDOWS

Users can use a circle gesture to post an orange house icon tag and click the tag to show the media info window. Figure 6 shows four highlighted regions and the user can click the tag icon. Then the media info window will pop out on the screen. The information includes house content, house photo/video, and house location on Google Maps (Figure 7). All information is directly connected to a database and an on line map. The media info window uses multi-touch advantages to show details and to compare different cases.

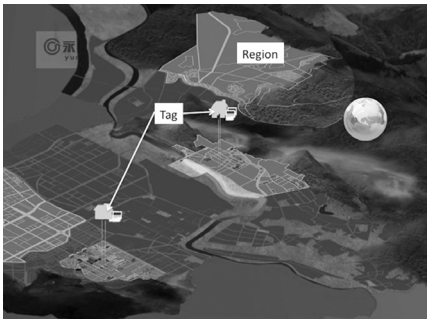


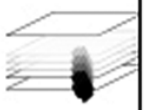
Figure 6. City map shows 4 regions and tag icon.

Figure 7. The media window give contain different type data format.

5. Result

After the implementation for the MTHI system we provide five gestures: Drag, Zoom, Mark, Delete, Pull (Table 1). Based on regular multi-touch functions we redefined three gestures: "Mark": the user draws a circle on the target building; the orange house tag icon shows the link on it. "Delete": user draws a cross on the orange house tag icon for the icon to disappear. "Pull": user pulls the different topic layers from the main region layer, by sticking a finger on the chosen layer and position it vertically on the screen where ever the user wants as long as the finger stays in contact with the screen.

TABLE 1. Five gestures of MTHI.

Item	Drag	Zoom	Mark	Delete	Pull
Gesture					

6. Conclusion and future work

In this paper we present the MTHI-a multi-touch wall. The key contribution is the redefinition of the gestures used for real estate filed. And this system has been running from 2009 until now. It shows that the MTHI system really answered the needs of house sale's procedures. But today the MTHI system is an expensive installation. For the future we try to decrease the total cost and the projection distance. That will achieve the market request.

Acknowledgements

This project for Xxtralab design is a new experimentation in the real estate field. We appreciate Yungching real estate Company using these innovative ideas. And thanks to the members in charge on this projects Lin, G.D, Lional Hsiang, I-Di Yen. We realised the first house information system on 190" multi-touch screen in Taiwan.

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SOAR: SENSOR ORIENTED MOBILE AUGMENTED REALITY FOR URBAN LANDSCAPE ASSESSMENT

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Abstract. This research presents the development of a sensor oriented mobile AR system which realises geometric consistency using GPS, a gyroscope and a video camera which are mounted in a smartphone for urban landscape assessment. A low cost AR system with high flexibility is realised. Consistency of the viewing angle of a video camera and a CG virtual camera, and geometric consistency between a video image and 3DCG are verified. In conclusion, the proposed system was evaluated as feasible and effective.

Keywords. Landscape assessment; augmented reality; mobile device; geometric consistency; GPS.

1. Introduction

In recent years, the need for landscape assessment for public projects, high-rise buildings or high voltage transmission towers has been growing. A landscape assessment means that a project executor hears various opinions, evaluates them, and includes some of them in the project. They help to create a new, good landscape by inclusion in the project execution in each project phase, such as the conceptual phase, planning phase, design phase and maintenance phase. A review meeting of landscape assessment is carried out on a planned construction site in addition to being carried out in a conference room. A landscape is constituted by two or more elements such as artificial objects and natural objects. It is difficult for stakeholders, such as project executors, academic experts, and residents, to imagine concretely such an image that is three-dimensional and does not exist. Therefore, a landscape simulation

method using visualisation systems such as Computer Graphics (CG) and Virtual Reality (VR) has been developed. Traditional perspective drawing, photo montage, and physical models have the problem that the adaptation to change takes time, compared to other digital landscape simulation methods. Moreover, 3DCG perspective drawing or animation has the problem that it is difficult to review immediately from the viewpoint that the reviewer wants at the time of a meeting. In order to check whether some portions of high structures are visible or not behind the locations of interest from multiple viewpoints in the landscape assessment process, it is necessary to make a 3D model representing the geography, existing structures and natural objects using 3D CAD or VR software. However, it usually requires much time and expense to make such a 3D model. Moreover, since consistency with real space is not achieved when using VR on a planned construction site, it has the problem that a reviewer cannot get an immersive experience.

Thus, in this research, the authors propose a new method using Augmented Reality (AR) which can superimpose an actual landscape acquired with a video camera and 3DCG. If AR is used, a landscape assessment object will be included in the present surroundings, and it will become possible to carry out a landscape preservation study. Thereby, a drastic reduction of the time and expense involved in carrying out 3DCG modelling of the present surroundings can be expected. In AR, realisation of geometric consistency with a video image of an actual landscape and CG is an important feature (Viet et al. 2009, Charles 2010, Ming 2010, Suyang 2010). The following methods are proposed: 1) use of physical sensors such as the Global Positioning System (GPS) and gyroscope, 2) use of an artificial marker, and 3) the extraction of characteristic points. In method 1), in order to realise highly precise geometric consistency, special hardware which is expensive is required (Fukuda et al. 2006, Leon et al. 2009, Watanabe 2011). That is, a problem remains in utilisation since equipment is required that not all people may have. In method 2), geometric consistency is realised using an artificial marker which can be made at low-cost (Yabuki et al. 2011). However, since an artificial marker needs to be always visible by the AR camera, the movable span of a user is limited. Moreover, in order to realise high precision, it is necessary to use a large artificial marker.

In this research, a smartphone that is widely available on the market level is adopted as an AR device. SOAR (Sensor Oriented Mobile AR) system which realises geometric consistency using GPS, a gyroscope and a video camera which are mounted in a smartphone is developed. A low cost AR system with high flexibility is realisable through this research.

2. System development

2.1. DEVELOPMENT ENVIRONMENT OF A SYSTEM

The authors use a standard spec smartphone, a SoftBank 003SH running Android 2.2. Development languages are OpenGL-ES ver.2.0 and Java ver.1.6. The development environment is Eclipse Galileo ver.3.5.

2.2. SYSTEM FLOW

The flow of the developed system is shown below (Figure 1).

1. Rendering of a video image is described. While the CG model realises ideal rendering by the perspective drawing method, rendering of a video camera produces distortion. Therefore, it is necessary to calibrate the video camera using Android NDK-OpenCV.
2. The definition of a 3DCG model which is the target of landscape assessment is described. Firstly, in a 3DCG model, the geometry (.obj) and the unit of the 3DCG model are described. Secondly, in a 3DCG model allocation file, the name, the file name, the position data (longitude, latitude, ellipsoidal height), the degree of rotation angle, and the zone number of the rectangular plane of the 3DCG model are described. Finally, in a 3DCG model the allocation list file, the number of the 3DCG model allocation information file and each name in the 3DCG model arrangement information file are described.
3. A system user selects a 3DCG model that will create a landscape assessment object using the GUI of a smart phone.
4. After the 3DCG model is selected, acquisition of the position information (latitude, longitude, ellipsoidal height) and angle information (yaw, pitch, roll) of the user's present location is started with GPS and the gyroscope in the smart phone. Moreover, acquisition of a live video image of the present location is started with a video camera.
5. The definition of the position and orientation data on a CG virtual camera which renders 3DCG is described. The position data (longitude, latitude) acquired by the GPS mounted in the smartphone is converted into the coordinates (x, y) of a rectangular plane. Orthometric height is created by subtracting the geoid height (Geospatial Information Authority of Japan 2011) from the ellipsoidal height acquired by the GPS. Angle values of yaw, pitch, and roll are acquired by the gyroscope mounted in the smartphone. A yaw value points out magnetic north. In an AR system, in order to use a true north value, a magnetic declination is acquired and corrected.
6. A 3DCG model is made to superimpose on the live video image of a video camera.

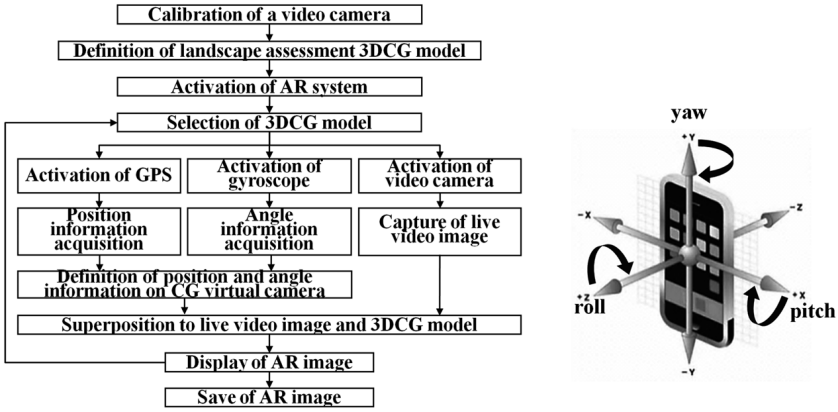

Figure 1. System flow (left) and Coordinate system of developed AR system (right).

3. Verification of the system

Verification of the developed system is described. In this research, consistency of the viewing angle of a video camera and CG virtual camera and accuracy of the geometric consistency of the video image and 3DCG are verified.

3.1. CONSISTENCY WITH THE VIEWING ANGLE OF A VIDEO CAMERA AND CG VIRTUAL CAMERA

In order to realise geometric consistency between a 3DCG model and a live video image, firstly, it is necessary to uniform the viewing angle of CG virtual camera and a video camera. Although the viewing angle of the video camera is a fixed value, since it is generally not shown to the public, the consistent viewing angle is discovered through an experiment.

3.1.1. Experimental methodology

First, both a rectangular parallelepiped physical model and a 3DCG model of the same size were prepared. Next, the physical model was installed at a position where the distance from the video camera would be 1 m, 3 m, and 5 m, respectively in that order. In an analogous way, the 3DCG model was installed in a position where the distance from the CG virtual camera would be 1 m, 3 m, and 5 m, respectively in order. Then the live video image of the physical model and the 3DCG model are rendered simultaneously. The width and height of the physical model and the 3DCG model which are rendered were measured. The viewing angle which showed the smallest value of both differences in dimension was the viewing angle to determine. In this experi-

ment, the horizontal viewing angle of the CG virtual camera had three options: 37.1 degrees, 37.2 degrees, and 37.3 degrees, and it measured 5 times per each distance.

3.1.2. Results

The size of the 3DCG model was about 0.02 times as large as the physical model when the horizontal viewing angle of the CG virtual camera was 37.1 degrees. The size of the 3DCG model was about 0.0003 times as large as the physical model when the angle was 37.2 degrees. The size of the 3DCG model was about 0.003 times as small as the model when the angle was 37.3 degrees. As a result of the experiment, the horizontal viewing angle of the CG virtual camera obtains 37.2 degrees.

An experimental photograph for which the horizontal viewing angle of CG virtual camera was set at 37.2 degrees is shown in Figure 2. The ratio (3DCG model / physical model) of the width and height is shown in Figure 3.

Figure 2. Experiment photograph (Black rectangle: 3DCG; White rectangle: physical model).

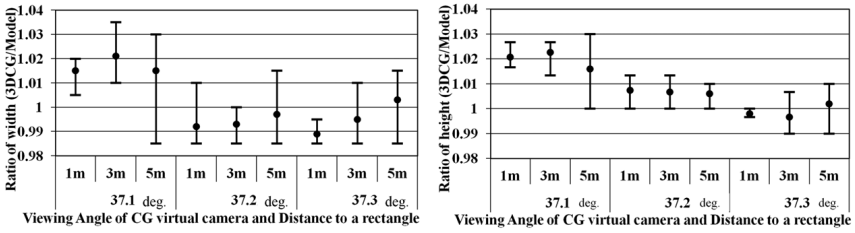

Figure 3. Ratio (3DCG model/physical model) of the width (left) and height (right).

3.2. ACCURACY OF GEOMETRIC CONSISTENCY WITH A VIDEO IMAGE AND 3DCG

3.2.1. Experimental methodology

The parameters for realising geometric consistency are the position information (latitude, longitude, ellipsoidal height) acquired by GPS, and angle infor-

mation (yaw, pitch, roll) acquired with a gyroscope. The accuracy of geometric consistency is determined by combining the residual error of these parameters. First, what kind of detection characteristic each parameter showed was identified. Therefore, a landscape viewpoint place with known position information and angle information was set up. In one experiment, only one parameter was acquired from a device and the remaining parameters set up a known value as a fixed value. A 3DCG model created from the design drawing was made of an existing building to superimpose on the live video image, and the residual error was measured.

Consequently, eight experiments were conducted in this research (Table 1). In experiment No. 1, all the data on the latitude, longitude, ellipsoidal height, yaw, pitch, and roll of the CG virtual camera used known static values. In experiment No. 2, all the data on the latitude, longitude, ellipsoidal height, yaw, pitch, and roll of the CG virtual camera used dynamic values acquired from GPS and a gyroscope slope. The dynamic values acquired from GPS and a gyroscope slope were used only for one parameter among the latitude, longitude, ellipsoidal height, yaw, pitch, and roll of the CG virtual camera, in experiment No. 3 to No. 8; the remainder used the static values.

In this research, the GSE Common East Building of Osaka University (W29.6 m, D29.0 m, H67.0 m) was used as a landscape assessment object. As a landscape assessment viewpoint place, No.14-563 reference point ((latitude, longitude, orthometric height) = (34.82145699, 135.519612, 53.1)) in Suita city, from where the GSE Common East Building can be seen, was used. The distance from the reference point to the centre of the GSE Common East Building was 203 m. An AR system was installed with a tripod at a level height 1.5 m from the ground. An experiment photograph and measuring points of residual error are shown in Figure 4. The experiment condition is shown in Table 2.

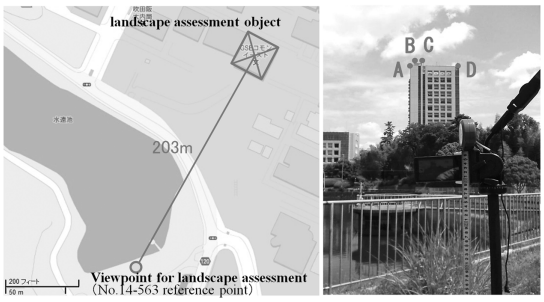

Figure 4. Experiment plan (left), photograph and measuring points of residual error (right).

TABLE 1. Parameter setting in the experiment (S: Static value; D: Dynamic value).

Experiment	Position information of CG virtual camera			Angle information of CG virtual camera		
	latitude	longitude	ellipsoidal height	yaw	pitch	roll
No.1	S	S	S	S	S	S
No.2	D	D	D	D	D	D
No.3	D	S	S	S	S	S
No.4	S	D	S	S	S	S
No.5	S	S	D	S	S	S
No.6	S	S	S	D	S	S
No.7	S	S	S	S	D	S
No.8	S	S	S	S	S	D

TABLE 2. Experiment condition.

Experiment time	Sep. 18, 2011, at 12:00 – 15:00
Weather	Fair, occasionally cloudy
Equipment	Smartphone (003SH), tripod, measure

3.2.2. Calculation procedure of residual error

The calculation procedure of residual error at the measuring point is shown.

1. The AR image was captured, and four corners of the building on the live video image were set to the measuring points of residual error A, B, C, and D. Each difference between the horizontal direction and vertical direction of those points and the 3DCG model was measured in terms of the number of pixels (Δx, Δy). This is called a pixel error.
2. From the acquired value (Δx, Δy), each difference in the horizontal direction and vertical direction was computed as a meter unit by the formula 1 and the formula 2 (ΔX, ΔY). This is called a distance error.

$$\Delta X = \Delta x \cdot W / x \tag{1}$$

$$\Delta Y = \Delta y \cdot H / y \tag{2}$$

W: Actual width of an object (m), H: Actual height of an object (m), x: Width of 3DCG model on AR image (px), y: Height of 3DCG model on AR image (px)

3.2.3. Results

- In experiment No. 1, the pixel error was 1.5 pixels or less, and the mean distance error was less than 0.15 m. From this result, the accuracy of the AR

drawing of a system was found to be high and it is suggested that an object 200 m away can be fully evaluated when a known static value is used (Figure 5 left and Figure 6).

- In experiment No. 2, the pixel error was less than 20 pixels in the horizontal direction and less than 55 pixels in the vertical direction. The mean distance error was 2.3 m in the horizontal direction and 6.3 m in the vertical direction (Figure 5 right and Figure 6).
- In experiment No. 3, only the latitude data of the CG virtual camera used the dynamic value acquired from GPS. The pixel error was less than 23 pixels in the horizontal direction and less than 14 pixels in the vertical direction. The mean distance error was 2.6 m in the horizontal direction and 1.6 m in the vertical direction. In this experiment, the object was north-northeastward from the viewpoint. Therefore, when the latitude was made into a dynamic value, a 3DCG model was drawn so that it might be expanded and reduced (Figure 6).
- In experiment No. 4, only the longitude data of the CG virtual camera used the dynamic value acquired from GPS. The pixel error was less than 97 pixels in the horizontal direction and less than 11 pixels in the vertical direction. The mean distance error was 11.2 m in the horizontal direction and 1.2 m in the vertical direction, and shifted horizontally (Figure 6).
- In experiment No. 5 and No. 7, the vertical pixel error was large. That is, if an ellipsoidal height or pitch is made into a dynamic value, the position of 3DCG model will move up and down (Figure 7).
- In experiment No.6, only the yaw data of the CG virtual camera used the dynamic value acquired from the gyroscope. The pixel error was less than 115 pixels in the horizontal direction and less than 5 pixels in the vertical direction. The mean distance error was 13.2 m in the horizontal direction and 0.6 m in the vertical direction, and shifted horizontally greatly (Figure 7).
- In experiment No. 8, only the roll data of the CG virtual camera used the dynamic value acquired from the gyroscope. The pixel error was less than 14 pixels in the horizontal direction and less than 5 pixels in the vertical direction. The mean distance error was 1.6 m in the horizontal direction and 0.5 m in the vertical direction, and this parameter had a small influence on the residual error (Figure 7).

Figure 5. AR screen shot of experiment No.1 (left) and No.2 (right).

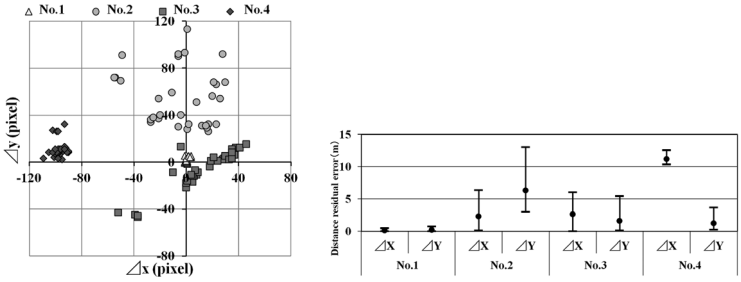

Figure 6. Pixel error (left) and distance error (right) in experiment No.1, 2, 3, and 4.

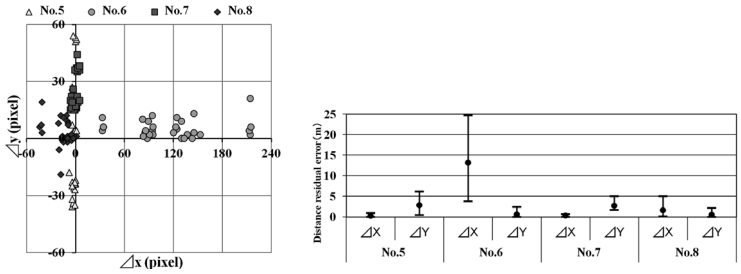

Figure 7. Pixel error (left) and distance error (right) in experiment No.5, 6, 7, and 8.

The mean distance error acquired in each experiment is shown by the absolute value in Figures 6 and 7. Although No. 2 is all dynamic inputs, the X residual error of No. 2 is smaller than the one of No. 6, for example. Namely, it is the result of offsetting the X residual error of No. 2, the X residual error of No. 6 etc. which is + angle, and the X residual error of No. 4 etc. which is – angle.

4. Conclusion

The contributions of this research are as follows:

- The developed AR system has geometric consistency using GPS and the gyroscope with which the smart phone is equipped. Therefore, a user can use it easily and we can describe it as a system with high flexibility.
- The horizontal viewing angle of the CG virtual camera for realising highly precise geometric consistency was 37.2 degrees. Moreover, when a known value was used for the position information, and the angle information on the CG virtual camera as a static value and the distance between the AR system and an object was 200 m, the pixel error was less than 1.5 pixels, and the mean distance error was less than 0.15 m. This value is the tolerance level of landscape assessment. On the other hand, when the dynamic value acquired with GPS and the gyroscope was used, the pixel error was less than 20 pixels in the

horizontal direction and 55 pixels in the vertical direction. The mean distance error was 2.3 m in the horizontal direction and 6.3 m in the vertical direction.

- The characteristic of the residual error which each parameter acquired with GPS and the gyroscope has been analysed. When the error of GPS is large, it is corrected by carrying out direct entry of the numerical value.

A future work should attempt to reduce the residual error included in the dynamic value acquired with GPS and the gyroscope. Moreover, it is also necessary to verify accuracy of the residual error to objects further than 200 m away and usability.

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5A GENERATIVE, PARAMETRIC, AND EVOLUTIONARY DESIGN II

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GENERATIVE SYNTHESIS SYSTEMS

A framework

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Abstract. Responses delivered by a generative synthesis system (GSS) vary between creative solutions and unusable outcomes. The type of GSS response is driven by many factors such as: the design context, designer's interpretation, implementation environments, design language, and the GSS composition, among many factors. In this paper, we describe a GSS framework to provide a recipe for delivering responses, which can be qualified as solutions. The framework focuses on GSS composition. It includes descriptions for: building blocks, components, and building strategy. The framework is informed by generative design literature and by our experimentation. We present the framework through: a brief background to GSS, metrics, building blocks, components, and building strategy. We also show an example of GSS implementation and offer a brief discussion.

Keywords: Generative; building blocks; components; strategy.

1. Introduction

In this paper, we use the term generative synthesis system (GSS) to refer to a composition or a structure that is capable of delivering alternative responses to a design context. Internal interactions among GSS elements and external inter-

actions with design context elements formulate these Responses. Responses can vary between two states: acceptable solutions and unusable outcomes—including "nothing" outcomes. Furthermore, we present synthesis as a process that leads to composing a scheme or a group of related elements. In addition, we distinguish synthesis from optimisation in that the latter deals with making tradeoffs between input values to find responses that are "more successful". As such, topics like Genetic Algorithms, Evolutionary Computing, Neural Network and the likes are not a part of the discussion in this paper.

2. Background

The formalisation of generative synthesis originates from Chomsky's early work on formal grammars (Chomsky 2002); Stiny, and Gips on Production Systems and Shape Grammars (Gips and Stiny 1980); Krishnamurti on the arithmetic and computerised generation of shapes (Krishnamurti 1978); March on architecture and geometry (March 1974); Lindermayer on growth rules and systems (L-Systems) (Lindenmayer 1975); and Simon on representation (Simon 1996). Applications of GSS include, but are not limited to, the following:

- Reproduction of architectural styles such as Malagueria Houses Grammar (Duarte 2005) and Boundary Solid Grammar for generating Queen Anne Houses (Heisserman and Woodbury 1993).
- Production of Architectural vocabulary such as COlumn DEsigner (Liebich 1994), Site and urban planning such as SIPLAN (Yessios 1975) and Marrakech Medina Grammar (Duarte et al. 2007).
- Architectural Detailing such as Knowledge-based architectural detailing systems (Radford and Gero 1985).
- Shape Emergence and form finding such the work done on Shape Grammars for form finding[1] and Rationalisation of form[2].
- Modeling and Simulation of growth patterns and dynamic systems behavior such as L-systems (Lindenmayer 1975) and Cellular Automata (CA) (Wolfram 2002).

3. GSS Metrics

Describing GSS in metrics leads to building type definitions, which are valuable because they help designers: (1) formulate an understanding of the GSS they are creating, and (2) indentify methods to enhance the GSS capacity and

1 Examples on form finding with Shape Grammars include the work of Stiny, Knight, Frazer, Economou, Kostas, and Rahim, among others.

2 Examples on rationalization include the work of Sheldon, Flöry, Pottmann, and Killian, among others.

response quality and quantity. In this section, we propose three metrics that are related to GSS composition—the focus of this paper.

3.1. ORGANISATION

This metric describes the scheme by which system components relate to each other. Suggested types are hierarchical, heterarchical, and integrated. These organisation types indicate decision-making mechanisms and, more broadly, how activities are performed in relation to one another.

In a hierarchical organisation, decisions flow vertically from top to bottom enforcing a Master-Slave like structure and implying nesting. In a heterarchical organisation, decisions flow horizontally enforcing an Equals-like structure where elements are at the same level (Duffie 1990). Integrated organisations are a mixture of the hierarchical and heterarchical types. Consider the following example: A GSS *alpha* generates house types by three methods: h1, h2, and h3. All house methods generate rectangular plans of different sizes. Each house method includes a unique nested garden method: g1, g2, g3. When reviewing the organisation of this GSS horizontally, a heterarchy is observed because all three methods play a similar role at the same level, and thus are *equal* and *independent* of one another. When reviewing each house method separately, the system displays a hierarchy because garden methods are subordinate to the *Master* house methods. Holistically, *alpha* displays an integrated organisation.

3.2. DEPENDENCY

We propose this metric to identify the type of dependency in the generation process. We note two types: Sequential generation and Parallel generation.

Sequential (dependent) generation is identified when successor responses are dependent on and can only start after the completion of predecessor responses. This notion is borrowed from the way Chomsky's grammars work on languages (Chomsky 1985). An example of sequential generation is how CA works, where a second iteration (generation) is possible only if the previous one is completed (Wolfram 2002).

Parallel (independent) generation of responses is performed by breaking a response into smaller chunks, where each is generated simultaneously and then they are merged into one (Hornby and Pollack 2001). This is similar to how L-Systems work where strings are generated by replacing alphabets simultaneously then concatenating them into a new string (Lindenmayer 1975).

Similar to Organisation, Dependency can be a mixture of the suggested types. It is important to note that this system property is highly affected by the type and structure of representations used to describe the design solutions.

3.3. REPRESENTATION TYPE

This metric describes the type of representation used in the GSS. Representation is a structure of symbols that expresses the environment or design intent through a set of mapping rules (Kalay 1989). We suggest the following types: Fixed, Parametric, or Aggregated.

We define a *fixed* representation as a set of elements and properties, which remain fixed throughout the generation process. An example on fixed representation is CA where cells have a fixed structure and property sets. We define *parametric* representation as a fixed number of elements, and changeable property sets. An example on parametric representation is a NURBS curve, which is represented by a fixed number of control points that can receive varying values of curvature and weight. Lastly, we define an *aggregated* representation as a variable set of elements and a variable set of properties. An example of what we call aggregated representation is Shape Grammars (Stiny 1993).

4. GSS building blocks

In this section, we identify the building blocks used for constructing GSS.

4.1. DESIGN OBJECTIVES AND DESIGN LANGUAGE

Defining design objectives is essential for exploring generative synthesis (Yessios 1975) for they help define stages and types by which activities can be carried out and organised (Minsky 1988). Design-languages help define the nature and characteristics of the design solutions. A single design solution can be expressed by more than one design language even if it serves only a single design objective (Stiny and March 1981). Thus, it is possible to create a GSS, which uses multiple design languages to aggregate alternative design solutions to serve a single objective. Defining the objectives and language, even if at a general level, can help greatly in defining the characteristics of solutions, as well as the GSS itself.

4.2. ALGORITHMS AND RULES

An algorithm is a series of mathematical or logical steps carried out to solve a problem (Terzidis 2006). It is possible to represent algorithms via mathematical formulas (quantities, symbols, and arithmetic relationships), verbally by spoken language, graphically by shapes, among others. Designers can control algorithms by implementing rules. Rules often expressed in “If–Then” statements representing required conditions to take possible reactions (Cormen et al. 2009).

4.3. PARAMETERS AND DATA TYPES

Designers may view parameters as placeholders or containers of data, which can be fixed or variable. When developing a parameterisation scheme, it is good practice to associate parameters with one another. Associating parameters will introduce different forms of dependency inside the GSS. This offers different forms of control and provides methods to conceal certain parameters while exposing others (Alfaris 2009).

4.4. DATA STRUCTURES AND REPRESENTATION

We define a data structure as a composition of data arranged in a pattern or a logic, which facilitates storage, query, and retrieval of data. Data structures are mostly application-driven; each performs differently under different circumstances (Cormen et al. 2009). In Computer Aided Design, geometric entities can be considered Data Structures as described by Eastman (Eastman 1976, 1981), Heisserman, (Heisserman and Woodbury 1993), Stiny (Stiny 1993) and Gero (Radford and Gero 1985). Representation is a scheme, which maps packages and maps properties of the environment into a set of symbols and relationships (Kalay 1989). GSS designers can arrange properties in various data structures to create multiple representations of elements created by the GSS.

5. GSS components

Drawing from the work of Gips and Stiny on Production Systems (Gips and Stiny 1980), we propose a GSS framework of three components: Goals & Sequences; Repositories; Interpreters; and Interfaces. These components describe roles rather than boundaries of discrete system entities. These components are constructed by the previously described *building blocks*.

5.1. GOALS AND SEQUENCES

Goals and sequences represent the skeleton of a GSS. They define the objectives and the stages within which other GSS components must deliver possible solutions. This will also help ensure progression within the GSS and identification of a final solution. This will also prevent the process from entering into an endless search or an infinite loop.

5.2. REPOSITORIES

Repositories are composed of data structures and algorithms for searching, querying, editing, and modifying stored data. Repositories are used to manage different types of GSS building blocks, and outcomes.

5.3. INTERPRETERS

Interpreters help formulate suitable responses based on evaluating the evolving context of the design problem and the generated outcome. Responses can be in the form of triggering element creation algorithms, building different representations, activating more constraints, carrying out further analysis, implementing alternative evaluation methods, or even stopping the generation process from proceeding further causing the GSS to stop.

5.4. INTERFACES

Interfaces define the methods and protocols by which interactions take place internally among GSS components, and externally between the GSS and users. User Interfaces allow designers to take part in the generation process by making joint-decisions with the GSS through the selection of parameter values, algorithms types, elements, etc.

6. GSS building strategy

Gero defines the goal of design as the production of design descriptions. This goal can be achieved through a sequence of activities: formulation, synthesis, analysis, evaluation, reformulation, and production of a design description (Gero 1990). We draw from Gero's description of the design process a series of activities to build a GSS system. We believe that designers ought to explore these activities both in parallel and in sequential orders because design processes are not always linear. However, it is important to enforce methods that ensure progression towards potential solutions.

6.1. DEFINING SCOPES

In this activity, designers collect information and build definitions for: (1) the potentials and constraints in the design context, (2) the desired goals, (3) methods to evaluate GSS responses, (4) and the attributes of the delivered design languages.

6.2. FORMULATING DESIGN RULES AND SEQUENCES

This activity requires an initial understanding of the design problem. Thus, we recommend carrying it out in parallel to or after *defining scopes*. Designers describe stages through which a design evolves, as well as the rules related

to each stage. This will enable the designer to focus on each stage as a new, smaller, design sub-problem. Each sub-problem becomes an environment to explore building further layers of design rules. We recommend that designers map the type of outcomes (variations) possible in each stage to help assess the capacity of the system.

6.3. DEFINING REPRESENTATIONS

We recommend that designers define representations at different levels, and for different purposes based on what the design rules and algorithms require. Consider this example: a designer is developing a GSS to propose alternative evacuation routes and exit nodes for city A. He or she can incorporate data from a GIS city map (the context) such as information to describe the context of the system: existing street routes; rush hour times and durations; and population densities at various locations in city A. Furthermore, designers can represent the generated outcomes (evacuation routes and nodes) as series of graph diagrams (nodes and arrows), and networks of geometric lines.

6.4. IMPLEMENTATION

We suggest that designers carry out the initial GSS implementations through Shape Grammars manually. After a general GSS structure starts to form, we suggest that designers explore automating GSS components in a discrete fashion using a mixture of CAD modeling Macros, Parametric Modeling, Scripting, and Spreadsheet tools. This will help identify the environments most suitable for implementing each GSS component. If designers chose to work with different environments, they must focus attention on creating links between these components and environments. The type of GSS representations will have a great impact on how accurate, effective, and robust these links are.

7. Results of an example GSS implementation

In this section, we show some results of an experimental GSS, Concept House Generator (CHG). We built CHG to explore alternative conceptual designs for a house that conforms to a design language that satisfies the requirements of a subject (client). We built CHG as per the framework we propose: Goals and Sequences; Repository; Interpreters; and User interfaces. A sample of the generated results is included below in Figures 1 and 2.

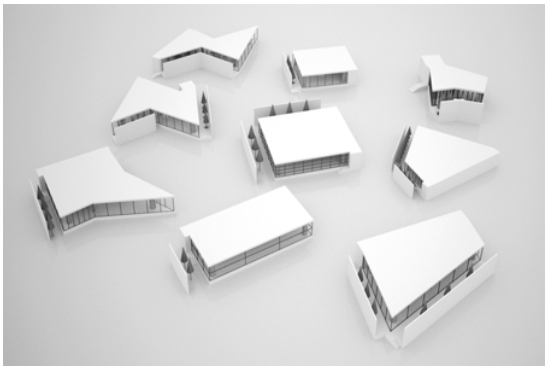

Figure 1. Different concept design proposals delivered by a CHG.

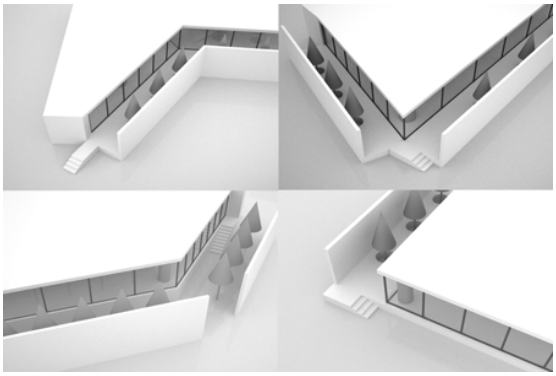

Figure 2. Different house entrance proposals delivered by a CHG.

8. Discussion

When formulating an understanding of the design context, we recommend that designers take advantage of the ill-definitions they find. We also recommend that designers seek a balance between the amount of rules, parameter ranges, constraints, and the various levels of goal definitions. It is possible to reach such a balance by iterative editing and testing of the GSS.

We believe that designers should not restrict the GSS to using only one formalism, one type of algorithm, or one kind of representation. For example, designers can deploy a CA model to implement a self-organising set of agents, while representing their attributes in a compact fashion using an L-system model. In addition, designers may describe GSS element relationships in Graphs to facilitate neighbor-element search operations. Layering different systems, formalisms, methods, and representations in a GSS will enhance its

capacity to generate responses. We encourage designers to search for alternative methods to interpret the results and behaviors exhibited by GSS as opposed to using them as outcomes.

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A MULTI-AGENT EXPERT SYSTEM SHELL FOR SHAPE GRAMMARS

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Abstract. This paper proposes a multi-agent rule based architecture of a computational system for supporting generic work with shape grammars. The key ideas and technologies involved are presented. This computational system is being developed and will give support to an urban and architecture research based on shape grammar theories.

Keywords. Shape grammars; rule based systems; multi agent systems.

1. Introduction

During almost 40 years research in Shape Grammars has been focused in conceptual and theoretical aspects (Stiny and Gips 1972, (Stiny 1980a, 1990, 1992, 2001, Knight 1993) and in analysis (Stiny 1977, Stiny and Mitchell 1978, 1980, Knight 1989, Koning and Eisenberg 1981). Work has also been done in synthesis (Stiny 1980b, Heisserman 1994, Agarwal and Cagan 1998, Duarte 2005) and in developing algorithms for shape manipulation in the rule application processes (Krishnamurti 1980, 1981, 1992, Krishnamurti and Stouffs 1997). Only more recently investigation has been oriented to more practical aspects of computer implementation including interfaces and generic interpreters of shape grammars (Tapia 1999, Liew 2004, McGill and Knight 2004, Li et al. 2009). For an historic and panoramic perspective on shape grammars see (Chau 2004) or (Chase 2010). However, as far as we understand, shape knowledge within these specific design applications is represented in a procedural ad hoc way and is therefore too rigid for further improvements.

We believe that a declarative knowledge-based approach would offer more flexibility to face new design situations and improve shape reasoning capabilities.

This paper proposes Generic Shape Grammars (GSG), a multi-agent rule based expert system *shell* to computationally support generic work with Shape Grammars. We start by describing the GSG project, with its key ideas and technologies involved and then propose a computational architecture. Finally we mention the Emerg.cities4all project, an on-going research on urbanism and architecture based in shape grammar theories that will have the computational support of GSG and which will also offer an opportunity to test GSG in a practical scope.

2. The GSG project

Within this project we are developing a configurable and extensible computational system tool to support generic work with shape grammars (applicable to different fields, *e.g.*, design, architecture, creative composition, education). This system will provide support to analysis and synthesis of languages of designs, including style extraction and representation into shape grammars, automatic spatial relation driven, parsing/analysis and computer supported generation/synthesis. The main objective is to provide an expert system *shell* for developing shape grammars based systems, *i.e.*, a tool providing the minimum software machinery to develop such systems and also with a configurable computational architecture allowing application based extensions according to different domain subjects, specialists and users.

Our actual research in GSG is centred on a generic shape grammar interpreter for shape computing, with reasoning capabilities about shapes and shape spatial relations and shape emergence, with an intuitive visual and symbolic interface and with advanced options for more complex work. Of course, the declarative and symbolic representation of shapes plays a key role.

3. Technologies involved and system architecture

The system relies heavily on Artificial Intelligence and Distributed Artificial Intelligence techniques and tools: heuristics and heuristic search, symbolic programming, symbolic knowledge representation and reasoning, logic, Rule Based Systems (RBS; both forward and backward reasoning) (Russell and Norvig 2003) and agents and Multi-Agent Systems (MAS) (Weiss 1999). Human-computer interaction will also be relevant since there are three types of users:

- system specialist: builds and expands the *shell*;
- shape grammar specialist: with the *shell* builds a system applied to a specific area;
- common user: applies the system to create solutions in the specific area.

The computational system architecture is depicted in figure 1. There are two core modules, the *geom* and the *rbs* module, and an additional *interface* module. Basically, the *geom* and *rbs* modules together provide the shape computing and reasoning capabilities. The *interface* module provides communication with the user, including facilities for shape and rule input/output and edition, a shape grammar interpreter, and system customization and extension.

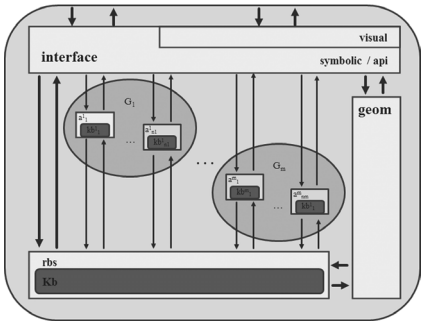

Figure 1. GSG architecture as a multi-agent rule-based system shell.

The *interface* has a visual component (a user interface) and a symbolic/programmatic component. The former is built on the latter, which is also available, as an API (Application Programmer's Interface), for the user, mainly for the system specialist or the shape grammar specialist, in order to allow for system customization and extension, and to develop specific shape grammar systems tailored to specific needs/applications.

The *geom* module provides operations on shapes (sub-shape and shape sum, difference and intersection and reduction to maximal shape) and shape transformations (translation, rotation, reflection, scale). The *rbs* module provides knowledge based representation and reasoning with shapes, shape spatial relations and shape emergence, and is built on a rule based expert system *shell*, with its inference engine and a global Knowledge Base. As shape grammars systems are essentially (forward reasoning) rule based production systems (dealing additionally with shape computation and emergence) it seems natural to use the rule based system paradigm here. Within an option for the shape grammar specialist and for complex problems, the GSG architecture borrows also concepts and practice from the MAS paradigm. The MAS paradigm views the problem solving effort as distributed amongst interacting autonomous, intelligent/proactive and/or reactive program modules, or agents. These agents can collaborate with each other in multiple coordinated ways ranging from purely cooperative to purely competitive.

In the GSG computational architecture there are (optionally) groups G_i of agents a^i_j, as shown in figure 1. Basically, these agents are RBSs through which complex shape grammar design problem data, computation and reasoning processes can be distributed. Which groups G_i will exist, or which specialist agents a^i_j will compose each group, in the system will depend on the application. For instance, in figure 2 we depict a possible instantiation

of the architecture just described for the Emerg.cities4all case, described in the next section. This multi-agent rule based architecture has already been sketched in some previous work (Reis 2008).

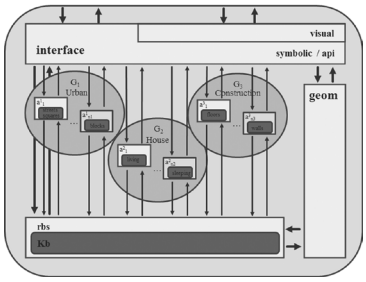

Figure 2. GSG architecture instantiated for the case of the Emerg.Cities4all project.

There are two main advantages of using the MAS paradigm here. First, a kind of emergence can happen where unexpected design solutions are generated when autonomous agent interaction in exploring parts of solutions in huge solution spaces comes into play. Second, in practical applications, huge and complex problem data, computations and reasoning processes may be conveniently distributed and modularized by using agents as the main module units. Different agents may be used with different specific roles and expert knowledge in a natural way for different practical aspects, such as: different drawing views (as in compound and parallel grammars), different stages of building a design, different levels of complexity of the language of designs (as in the hierarchy urbanism/architecture/construction), different tasks (as in drawing and colouring in painting), different styles, different roles in a design task (*e.g.*, generating, evaluating and criticizing, analysing), different parts of the computational system (*e.g.*, interface and presentation, interpreter and rule execution, shape operations, reasoning with shapes and spatial relations).

4. Emerg.cities4all

The Emerg.Cities4all is a research project being developed to generate urban and architecture designs. The project aims to produce a generative computer-aided planning system for cities in Portuguese-speaking countries in Africa and South America for low-income housing. It uses shape grammars as a descriptive method using GSG as a tool. Emerg.Cities4all will encompass several scales of intervention, ranging from the physical level of the city to the level of building construction. Modular, scalable, adaptable, customizable and affordable urban and housing unit solutions are the design goals. The proposed solutions must be environmentally sustainable and energy efficient, while respecting certain social and cultural qualities in the context of new Portuguese-speaking emerging urbanities. Several studies have been developed considering Architecture and Urbanism design but only few have been translated to a real computerized implementation using a shape grammar interpreter: on an architectural and construction level, the grammar of Queen

Anne houses (Flemming 1987), the Malagueira grammar (Duarte 2005), the Yingzao fashi grammar (Li 2002) and, on an urban level, the Marrakech Medina grammar (Duarte et al. 2007), CityZoom (Grazziotin et al. 2007) and City Induction (Beirão et al. 2010). These are some notable exceptions, which, nevertheless, present approaches different from ours. The main challenges of our approach are the ability to integrate flexibility and adaptability, supporting a larger number of conditions and constraints and being able to evaluate and control the results. In the Emerg.Cities4all project we are currently developing a declarative language that would be used to represent shape grammars and also agents, their behavior and interaction.

5. Conclusion

We described the key ideas, technologies and system architecture involved in the multi-agent rule-based expert system *shell* for shape grammars that we are developing. Symbolic knowledge representation and reasoning, Rule Based Systems and Multi-Agent Systems are the core in this system. These are important features, especially in applications where huge and complex problem data, computations and reasoning processes are involved.

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AN ALTERNATIVE PALLADIAN SHAPE GRAMMAR

A subdivision grammar for Palladian villas

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Abstract. This paper describes a shape grammar that recreates Palladio's villas. A Palladian grammar was previously proposed by Stiny and Mitchell. However, this alternative grammar uses different parametric shape rules and methodology to test the hypothesis that different grammars can generate the same corpus of designs. The formalism is then implemented using a computerised design tool. The grammar includes subdivision rules that allow for a more economical formulation. The project is part of wider research aimed at formulating a generic housing grammar.

Keywords. Shape grammar; design rules; housing grammar.

1. Introduction

This research paper describes the methodology used to recreate Palladio's design signature using a formalism called shape grammar. Stiny and Mitchell (1978a) illustrated the range of shape grammar and its first architectural applications. Thiswork replicates what was presented forty years ago, using

an alternative grammar and a computerised tool. The concept was applied to urban grammars to develop a partial generic urban grammar (Beirão et al. 2011).The novelty of this research lies in the hypothesis that more than one grammar can generate the same design solutions and if two separate sets of shape rules can produce the same solutions, this can be illustrated by generic rules enabling a generic grammar seems feasible.

The notion of grammars was widely discussed by the linguist Chomsky (Chomsky 1957). He describes how different languages with different roots encapsulate an innate sense of grammar and phrase formulation. The idea of a universal grammar explains these innate formulations.Subsequently, the notion of grammar was introduced into the field of geometry and algebra (Stiny 1975, 1980, 2011). A shape grammar is a structured formalism that incorporates a limited number of shape rules to describe geometric operations. These consist of an initial and a final stage, with a transformation, or geometric operation occurring between them. Combining different shape rules and ordering them into a shape grammar enables design styles to be recreated, such as the grammars for the Prairie houses (Koning and Eizenberg 1981), Siza's Malagueira houses (Duarte 2001), Ice-Ray Lattices (Stiny 1977) and the De Stjil paintings (Knight 1989).

According to Knight, there are three types of shape grammar processes: grid, addition and subdivision (Knight 1999). Grid grammars propose design generation based on a matrix. The design is derived from the grid using cell merging and subdivision processes. The original Palladian Grammar used a grid process to address the rectangular floor plan. In subdivision the solution is achieved through a succession of divisions and self-contained.

This alternative grammar uses a subdivision process. The justification for this is threefold: firstly, it represents a more intuitive way of designing, secondly, it allows for fewer shape rules and is more economical, easier to use, and thirdly it proposes a different process, thus proving that two distinct formulations can generate same results. The rule extraction process was based on observation of different existing villas, examining each floor plan, number of rooms, proportions, geometries, spatial adjacencies and communicating rooms. The layout of the floor plan for each villa uses 9 basic rules in contrast with the 25 used in the original grammar and all the shape rules have a parametric formulation. The initial rules define the boundary setting, whilst the rules that follow propose subdivisions. Other rules allow for the merging of consecutive cells by erasing borders. The design is completed by allocating centrally aligned openings in accordance with the original specifications (Palladio 1997).

Functions were not addressed in the original grammar, but were incorporated in this study. It was possible to identify the functions in unlabelled six-

teenth century villas by observing spatial adjacencies, using comparison as a method and taking proportion, shape and area into account. Notions of shape syntax integration and segregation were also considered (Hiller and Hanson 1984).

A computerised tool was created to provide non-shape grammar users a visual platform for exploring design. The script is easily accessible to CAD users and allows for real time 2D/3D design generation and visualisation.

Previous studies have proved that an extensive corpus of designs can be produced from limited design rules (Stiny and Mitchell 1978b). The original grammar allowed for the production of 220 solutions for grids of 5×3 cells. A generic grammar would allow for the design of more than one type of signature style and an extended corpus of solutions.

The relevance of this study is related to the wider aim of proposing a generic grammar for housing. Studies on grammars have been limited to illustrating specific styles but no two different grammars and rules sets have ever produced overlapping corpus. It is believed that there is more than one method for obtaining a grammar that incorporates style, confirming the hypothesis of shape grammars as broad formulations that can illustrate style.

This paper is organised into 6 sections. Section 2 explores the grammar formulation, whilst Section 3 describes the shape rules; 4 and 5 focus on the villa derivation and computer implementation respectively. The final section contains the conclusion and comments on the results.

2. Shape grammar formulation

A top-down approach was used in which the design process begins with the overall shape and evolves to further detailing. The self-contained boundary is set and a series of tasks are carried out to refine the design. The starting was the exploration previously inferred grammars. Using Knight's grammar classification, a case study was selected, comprising grid (Palladio), addition (Wright) and subdivision (Siza). The grammar structures were compared and the results led to a proposal that addressed the basics of housing design. The Palladian designed villas were studied and their generic features. A rectangular envelope constitutes the boundary and the villas are composed of a raised ground floor which contains the main social areas. A lower level ground floor contains the service areas, pantries, kitchens and servants quarters. The upper level contains living and bedroom areas for the house owner and family. The main floor is raised by steps and has more headroom, extending to the façade. This is the only floor plan usually illustrated and has been extensively studied by art historians so it is easily identified. The symmetry between the east and west wings is created by the north/south axis. The larger core area in the geo-

metric centre of the construction has a complex shape that is the result of cell merging. Windows (like the eyes in the human face) are arranged in even numbers whereas doors are centred and arranged in uneven numbers.

The main entrance is defined by a portico which enhances classical features of the façade typical of Renaissance architecture. The preferred proportions for the design of rooms, service and circulation areas are usually rectangular or oblong spaces with 1/2, 1/3, 1/4 ratios, whereas the main rooms are square, regular polygons, or rectangular areas with a 2/3 ratio (a proportion frequently adopted by established architects such as Aalto and Siza). The Malcontenta, Angarano, Badoer, Zeno, Pisani, Emo, Sarraceno, Ragona and Polana villas were used as case studies for rule extraction. Except villa Angarano, they all have a 3×5 grid. Both the original scheme (Figure 1) and the alternative (Figure 2) propose 8 design stages. The initial stage sets the rectangular boundary. The second stage encompasses subdivision rules. It groups together the two subdivision shape rules for horizontal and vertical formulation. Vertical subdivision is performed in accordance with the symmetrical nature of the design, introducing two division lines. Stage Four, which involves wall thickening, makes the basic outline two-dimensional. This stage deviates from the original grammar since in the latter the wall thickness was derived from the gaps between cells, whereas this grammar generates an abstract layout then makes it two-dimensional.

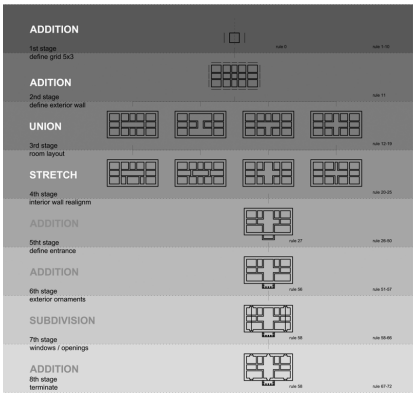

Figure 1. Original Palladian grammar derivation tree.

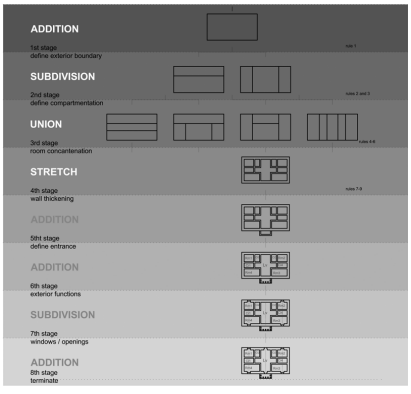

Figure 2. Proposed Palladian grammar derivation tree.

The fifth stage creates the entrance, consisting of a section extending from the core outwards to create an obtrusion. The definition of functional spaces, which had not been previously addressed, was fundamental and these were

introduced in the sixth stage. Whereas the oblong spaces are mainly circulation areas, the rectangular and square spaces opposite the façades are the living areas, and the central space is the social area. The seventh stage involved the subtraction of volumes for openings. Windows are arranged in even numbers and the doors in uneven numbers. Internal doors are usually centred within the circulation area taking a centre line as axis. There are different window sizes for the different levels, the larger sizes being on the main floor, followed by the top level, whilst the smaller windows are on the lower ground floor. The design is completed with a label deletion (a technical stage), which is the eighth and final stage.

3. Shape rules

The rule system proposes three types of rules: addition, subdivision and adjustment. The first rule proposes the addition of a rectangular overall shape, with parameterization based on the minimum and maximum acceptable areas, as illustrated (Figure 3). Subdivision rules include vertical and horizontal division, as exemplified in Rules Two and Three. These parametric rules represent the main operative process, allow for embedding (applied repetitively inwards or outwards) and can be used recursively (applied a number of times consecutively until the minimum usable space is attained). Subdivision rules respect the symmetrical design, hence the duplication of division in Rule Three.

Once the division has been executed, concatenation is used to arrange larger, complex spaces connecting adjacent rooms. To avoid unwanted space merging, these are applied only to borders, taking the adjacencies and symmetrical relations into consideration. The resulting space is displayed as an enclosed polygon. The west and east wings will be symmetrical. Deletion rules allow for the creation of complex spaces or a regular polygon boundary. Border deletion is achieved by using the forth fifth (horizontal and vertical) rules.

Wall thickness conforms to Palladio's specifications. The stone masonry construction used load bearing sheer walls as a tectonic method. The thickness of these walls is based on a generous safety coefficient that matches the construction grid lines and units. A depth of two Vicentine feet is prescribed for the walls (roughly 750 mm in metric system). The process is described in Rule Six, using an offsetting method. The desired wall centre will sit on top of the abstract layout.

Wall intersections are addressed in Rules 7 to 9, which propose the thickening of T, X, L combinations. Other addition rules add details, such as the entrance feature (porticos or loggias). These sets of rules are followed by other addition rules involving the inclusion of functions. The last set of rules

provides for alterations using volume subtraction to include openings. They involve the positioning of windows, which are arranged symmetrically, or the positioning of doors. Uneven numbers of external doors are centred in the façade and internal doors are created to connect rooms.

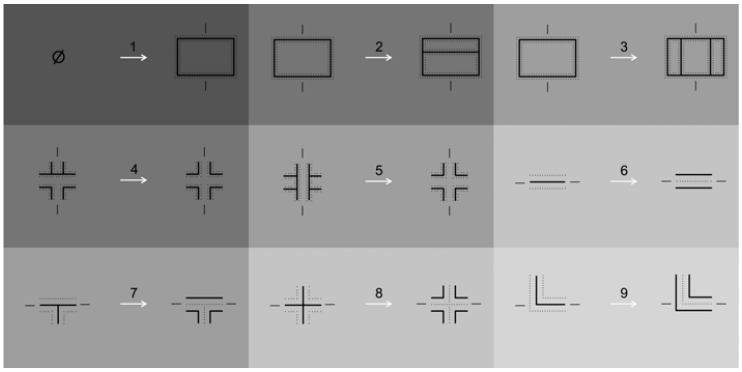

Figure 3. Proposed shape rules.

4. Villa derivation

Derivation describes the generation process in which the recursive application of shape rules leads to a final design. The original grammar showed how a successful design can be achieved, using the example of the derivation of the La Malcontenta villa (Figure 4). This was originally built between 1559–60 in Venice and is illustrated in Palladio's "Il quattolibbri" (Palladio 1997). In order to fully grasp the differences between the original and the alternative grammar, this was used for derivation. Despite the divergences (namely a more economical use of rules and process), both grammars contain the same number of stages. The new derivation process has 14 steps, using 10 shape rules sometimes recalled recursively (Steps 2, 5 and 6 using Rule Three, and Steps 3 and 4 using Rule Two).The first step is the boundary placement, followed by division in Steps 2 to 6. The division sequence of rules 3, 2, 2, 3, 3 splits a rectangle into three, or creates a variation of a 3×5 grid in which cells occupy a larger area for future occupancy. Step 7 deletes the vertical boundaries of the central cell. Step 9 offsets the preliminary layout by duplicating lines 2 feet away from each other and creating the wall placement. Step 10 deals with the intersections between wall lines and refines corners. Step 11 includes the entrance feature. Step 12 proposes functional uses by tagging each room. Step 13 creates openings in walls with the array or for window and doors. Step 14 terminates the design by erasing the labels.

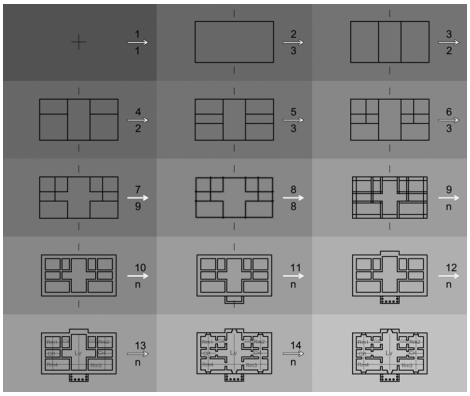

Figure 4. Derivation of the Malcontenta Villa.

5. Computer implementation

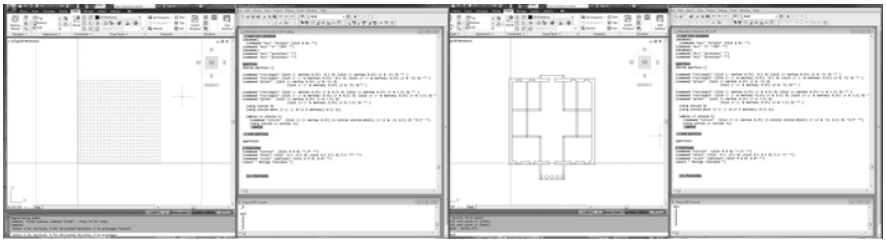

Figure 5. Computer implementation.

The computer implementation combines the shape rules, parametric formulation and conditions and actively assists in the complex application of the shape grammar. In addition, it reduces errors and secures the generation of solutions. Many languages were considered before AutoLISP, edited in VisualLisp, was selected as a dialect due to its object-based nature which facilitates implementation, using AutoCAD 2012 as a platform. The script was developed in a similar way to the grammar described in this paper (Figure 5). It focuses first on the plan view in 2D and then evolves to encompass the overall modelling of the villa, allowing for immediate visualisation of the design results in real time. The rules are implemented using different functions that can be called up recursively if desired and form and function are addressed sequentially. Stage 1 consists of the overall definition. The user is asked to choose the insertion point and area and the boundary is set using Palladio's proportion ratios, either a 1/1 square, a 1/2 rectangle or other appropriate ratios. The minimum and maximum areas are given as output and the user's input is opti-

mised to the proportional ratios. Once the boundary is drawn, an indicative matrix is inserted using Palladio's Vicentine measurements (1 ft ≈0.354 m). The dimensions are rounded off to this system and the proportions conform to symmetrical classical principles.

Stage 2 allows the user to intervene in the design of the interior layout. Subdivision rules allow for horizontal and vertical divisions and the mouse input is registered on screen, with location justified to the nearest possible position in the Vicentine matrix. Both rules can be recalled a number of times, restricted only by the remaining free space and maximum grid size. Stage 3 involves spatial concatenation using a process of cell border deletion. The user can erase lines to generate a larger room and the input is recorded and repeated when necessary to maintain symmetrical layouts. Stage 4 transforms indicative lines into masonry wall dimensions. The exterior walls will be 2 Vincentine feet deep and the interior walls 1 foot deep. The offset process takes the centre line drawn and reproduces two parallel lines in separate layers.

Stage 5 reads the design accomplished so far and positions and sizes the entrance and rear porticos, emphasising the north/south symmetry axis with a similarly sized central bay. Stage 6 creates openings in walls for doors and windows. Windows are added symmetrically to the façades in an arrangement corresponding to Palladio's specification for even numbers. Every room should have an even number of windows. Exterior doors are arranged along the symmetry axis of each façade in uneven numbers. Stage 7 involves the assignment of functions, accessing the data input and addressing functions in terms of spatial situation (central or peripheral), connectivity (first level connection), adjacency and type (living, social or distribution areas). Highly integrated spaces such as the central area connect with other rooms to create social areas.

Rooms positioned in corners and represented as squares or rectangles with ratios of preferably 2/3, 3/4, 4/5, 3/5, 1/2 are living spaces (studies or living rooms). Rooms between other densely connected spaces (i.e. with two or more connections) that are smaller and oblong (with proportions of 1/2, 1/3, or 1/4) are distribution spaces (circulation areas, corridors, staircases and antechambers). This function labels each space and creates the adjacency diagram by connecting the adjacent circulation areas.

6. Conclusion and future work

This paper presents an alternative grammar for the Palladian villas, offering a fourfold contribution. Firstly, it demonstrates that two separate sets of design rules can generate the same corpus of designs. Secondly, it proposes a more economical grammar. Thirdly, it introduces functions to the grammar.

Fourthly, it involves the development of a computer tool which provides a user-friendly environment for exploring design.

Shape grammars are useful formulations that provide support for design generation. Their use allows for consistency in design through specific sets of formal and functional rules. As a rule system, it provides a framework for consistent design generation. Research so far has focused on shape grammars for encoding specific styles and generating new designs within a given style. However, to the best of our knowledge, generic grammars that encode several design styles have not previously been inferred. The development of such grammars enables tools to be designed that facilitate the generation of designs within the same typology, such as housing. This work is the first step in this direction. It is part of an attempt to encode existing housing grammars into a similar grammatical structure in order to discover higher-level patterns that can be encoded and then customised. If two distinct set of rules can generate the same set of solutions (recreating a specific language), then a higher-level grammar might allow for the creation of different languages. This generic grammar, once refined, could encode specific design languages. Two issues were addressed in this work, form and function, or, alternatively, space and occupation. These very important aspects of architectural design were encoded into spatial transformation rules, enabling the user to progress from generic shapes to detailed designs, facilitated by the use of a computer tool that incorporates design knowledge. This tool was scripted using AutoLISP. These findings have potential uses both in architectural practice and design theory. Shape grammars have proved to be powerful tools for exploring design whilst maintaining stylistic consistency. The proposed grammar provides an alternative method for designing Palladian villas. It is an attempt to generalise the use of grammars and ideally create a generic set of parametric rules that can be adapted to different contexts. Future work will address these issues from the perspective of inferring a generic shape grammar for housing.

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REPRESENTATION OF TYPE IN GRAMMATICAL DESIGN

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Abstract. Grammatical design is useful for the generation of a set of related designs. The concept of type aids designers in generating designs with a specified structure. However, existing studies in grammar are ambiguous in their definition of type in the language of designs generated by a grammar. Extending our previous study of defining style in grammar, this paper provides a formal definition of the concept of type in the language of designs generated by a grammar. This is done with the help of a description scheme which is developed by augmenting grammar primitives and spatial relations with descriptors. The description scheme allows the computation of descriptors for designs generated from grammar thus making possible the comparison of various design types in the language of a grammar. Such a description scheme for defining design types is especially significant for less restricted grammars that generate a large number of designs that are varied in nature. A formal definition of type in grammars allows users to sift through designs with particular features, and thus select desired designs.

Keywords. Type; Design grammars; generative design; description scheme; product design.

1. Introduction

Shape grammars are an algorithmic system for the analysis and generation of designs through spatial computations. Grammars have been used to describe languages of design in the domains of architecture, product design and automobile design (Stiny and Gips 1972, Knight 1994).

Although grammars were invented forty years ago, their use in actual practice is fairly limited. One of the reasons for this is that it is difficult for users to predict the nature of designs generated by grammars (Knight 1980). Further-

more, often due to the large number and varied nature of designs generated by grammars, it is difficult for designers to find design solutions that match design goals. In order for grammars to be of practical use, it is important that designers working with grammars are able to generate designs with desired features.

The concepts of style are two commonly used devices for design analysis and synthesis. The former deals with sets of designs with similar aesthetics and mood, whereas the latter deals with the classification of designs based on parameters such as function and morphology (Krier 2003). For instance, a building type based on morphology is a courtyard type building, and building types based on function are airports, hospitals, museums etc. On the other hand, the concept of style transcends functional or morphological divisions – the Mackintosh style can be used to describe chairs as well as buildings.

We hypothesise that if formal definitions of concepts such as style and type are provided in the design language of grammars, it will be easier for designers to examine and select designs with desired features. However, the distinction between design style and type has been ambiguous in grammar literature so far and the two terms have been used interchangeably. A number of previous works have dealt with the ideas of paradigmatic and syntagmatic substitution in rule based systems (Carlson et al. 1991, Woodbury et al. 1992, Madrazo 1999). In continuation to our previous work in which we presented a definition of style in grammars (Ahmad 2009), in this paper we present a definition of type in grammars.

2. The concept of type in grammatical design

Type (2005) has been defined as "the general form, structure, plan, style, etc. characterising or distinguishing the members of a class or group or "a kind, class, or group having distinguishing characteristics in common". The concept of type is useful for not only analysis and synthesis of designs, but also it provides a basis for design evaluation. Although the origins of the concept of type lie in plant taxonomy, it has been beneficial for the classification and analysis of buildings as well.

Typological classifications may be done on the basis of function, form or design components (Achten 1997). Function-based classification involves grouping buildings on the basis of the function they fulfil. For example, types of public buildings are hospita ls, libraries and museums. A form-based classification is based on levels of spatial organisation. For example, houses may be classified as L-type houses, U-type houses or courtyard types. Component-based classification relies on topological analysis and groups design artefacts based on prominent design components. For instance, dwellings may be clas-

sified on the basis of their roofs such as flat roofed houses, two-way sloped houses, and single-slope roofed houses. Figure 1 shows examples of the aforementioned typological classifications.

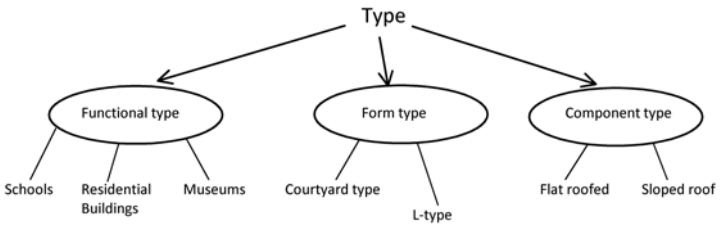

Figure 1. Examples of typological classifications.

Grammatical design is useful for the generation of a set of related designs. A corpus of designs is selected based on similarities in design elements. Rules are authored by reverse engineering to generate extant as well as new designs. Previous studies in grammars have often made use of the term 'style' to describe the set of designs generated by a grammar (Knight 1980, Chiou and Krishnamurti 1995). However, it has been argued that style involves the description of spatial features as well as aesthetic qualities of design artefacts (Ackerman 1963). Without the description of the latter, it is more apt to state that such studies deal with the concept of design type rather than style.

This raises the question whether a grammar generates only one type of design or many different types of designs? This study contends that the answer lies in the nature of the grammar and its rules. A small restrictive grammar with few rules would possibly generate designs of a particular type. On the other hand, a large unrestricted grammar could possibly host a number of design types. Thus, a formal definition of type would be extremely useful for designers as it would enable them to select designs with particular features.

In the following section, a method to define type in the design language generate by a grammar is demonstrated using the example of Greek temple façade design. The method relies on the use of a description scheme that augments verbal descriptors to grammar elements. First, the basic units of the design are identified and specified as primitives and spatial relations. Based on the concept of a set grammar with clear form-function decomposition, design rules are developed. Type descriptors of constituent primitives and spatial relations appended to them. Rules are then arranged hierarchically in function based rule sets, in order to support the generation of topologically valid designs.

3. Example of Greek temple grammar

The Greek temple design consists of a rectangular plan surrounded by a colonnade either all around, or towards the front and back. The façade of the Greek temple design primarily has three elements—a base, a set of columns, and a low pitched roof known as a pediment.

A rule base was authored for the design of Greek façade designs. It had rules that generated 'correct' sub-designs, as well as hypothetical designs. The rules were organised into six rule sets, depending on the operation carried out by the rules. Rule sets A, B and C have 'composition rules' that determine the location and positioning of primitive markers and their inter-relationships, i.e. the spatial relations. Rule sets D, E and F have 'specification rules' that decide the design of each element and articulate the compositional forms. The aforementioned rule sets were put together in a rule base consisting of 77 rules.

Two initial shapes were given. The initial shapes comprise of a set of orthogonal axes. Initial shape l included a set of markers on the opposite ends of the horizontal axis, indicating the extremities of the sub-design. These end markers are absent in initial shape 2. The two initial shapes present two different procedures of developing column sub-designs.

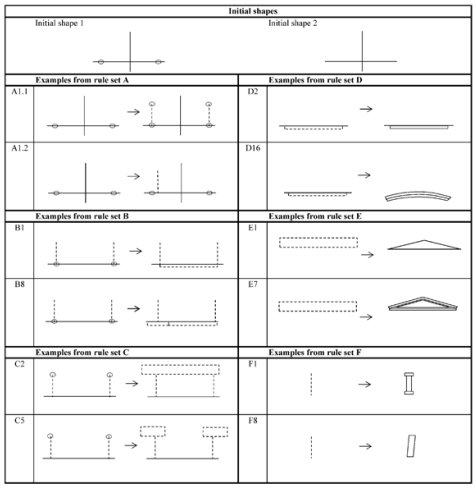

Figure 2. Examples of rules from each rule set.

Figure 2 shows the initial shapes given in the rule base and examples from each of the rule sets. Rule set A adds column markers to the sub-design. While rule set A1 is based on sub-division of the given length, rule set A2 adds columns in an outward fashion. Circular symbols identify the exterior most

columns on either side of the central axis. Rule set B has rules that add base markers underneath the exterior-most columns. Rule set C has rules that add the pediment marker over the exterior-most columns. Rule set D has 18 rules that modify the base marker into base designs. Rule set E has 18 rules that specify pediment designs. Rule set F has 18 rules that specify column designs. The complete set of rules is given in (Ahmad 2009).

The development of a correct facade design requires the application of at least one rule from each set. After the selection of an initial shape, composition rules are applied first, which place design element markers into the sub-design. Subsequently, specification rules are applied, which replace the markers with shapes specifying the design element.

A number of designs were generated from the rule base. Figure 3 shows some designs that were generated using the rules in the rule base.

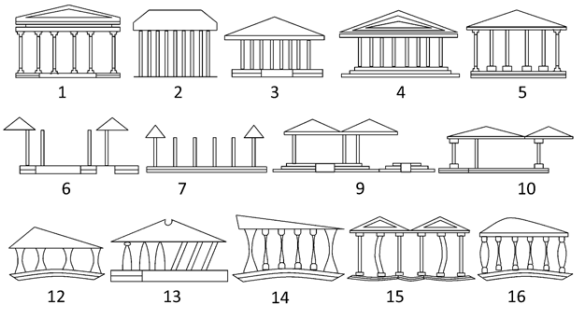

Figure 3. Examples of designs generated from the rule base.

4. A description scheme to define design type

A type description scheme was developed by modifying the style description scheme developed earlier in (Ahmad 2009) by retaining only the spatial characteristics of grammar elements. Verbal descriptions were assigned that described spatial relationship (in case of composition rules) or the design element (in case of specification rules) in the rule. Figure 4 shows an overview of the type descriptors chosen for the composition rules, specification rules and designs. For the purpose of this pilot study, straightforward binary descriptors were chosen and ascribed to grammar elements.

Based on the rules and the aforementioned descriptors augment to them, definitions were developed to describe design type in the language of a grammar. For the purpose of this work, only the description based on form-based and component-based classification of type has been attempted. These are described in the following sections.

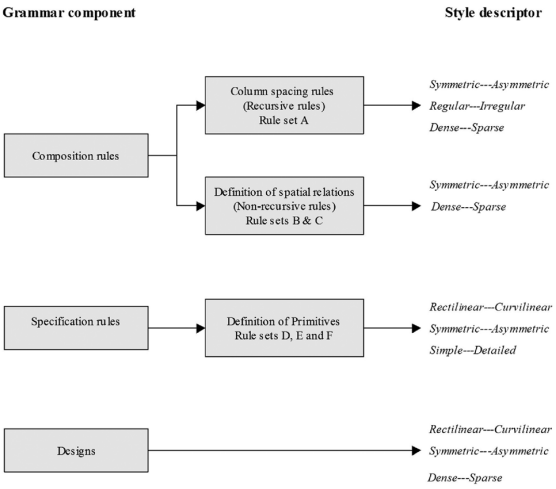

Figure 4. List of type descriptors.

4.1. COMPONENT BASED CLASSIFICATION

Firstly, component based classification of type may be defined using the rules present in the derivation of designs. For instance, T_1, a design type based on the double pediment roof type may be defined as the set of all designs that are generated using rules C2 and E7. Thus,

$$T_1 = \{D_d : d \ni (C2 \cup E7)\} \quad (1)$$

where D_d are designs with derivation d,

and C2 and E7 are rules in the rule base.

Designs 1, 3 and 4 fit this description.

Another example of this definition is T_2, a design type with a curved base. T_2 is defined as the set of all designs which are generated using rules B1 and D16. Thus,

$$T_2 = \{D_d : d \ni (B1 \cup D16)\} \quad (2)$$

where D_d are designs with derivation d,

and B1 and D16 are rules in the rule base.

Designs 12, 14 and 16 fall under this description.

Secondly, component based classification of type can also be defined using the primitive descriptor ranks augmented to the rules. For instance,

$$T_2 = \{D \ni PD_1 : PD_1 = -1\} \quad (3)$$

where D is designs generated by the grammar

and PD_1 is primitive descriptor 1 "*rectilinear---curvilinear*"

Designs 1, 3, 4 and 5 fall under this description.

4.2. FORM BASED CLASSIFICATION

Form based classification of design type may be defined in the following manner:

$$T_3 = \{D_d : d \ni (C5 \cup E1 \cup (F1x\ x))\} \quad (4)$$

where D_d are designs with derivation d,

C5, E1, E2 and F1 are rules in the rule base,

and x is the number of times a rule is repeated.

Designs 6 and 7 fall under this description.

Another type T_4 may be defined such:

$$T_4 = \{D_d : d \ni (A1.1 \cup A1.2 \cup C7 \cup (E3\ x\ 2) \cup (F1\ x\ x))\} \quad (5)$$

where D_d are designs with derivation d,

A1.1, A1.2, C7, E3 and F1 are rules in the rule base,

and x is the number of times a rule is repeated.

Designs 9 and 10 fall under this description.

Finally, form-based classification of type can also be defined using the spatial relation descriptor ranks augmented to the rules. For instance,

$$T_2 = \{ D \ni SR_3 : SR_3=1 \} \quad (6)$$

where D are all designs with spatial relation descriptor 3

and SR_3 is spatial relation descriptor 3 "*Dense—Sparse*".

Designs 6, 7, 9 and 10 fall under this description.

5. Discussion

This paper presented a possible method for the formal definition of design type in grammars. Three kinds of descriptors were developed to describe grammar elements: primitive descriptors, spatial relation descriptors and design descriptors. For the purpose of this pilot study, polar adjectival pairs with simple semantics were used for the description of three basic design elements. It is acknowledged that a complete description of design requires descriptors with greater detail. The purpose of the descriptors is to make explicit the qualities which are otherwise ambiguous in designs. Since the design problem was a fairly straightforward one, the use of simple semantics for the description risked stating the obvious. It is concluded that this method would be more suit-

able for larger grammars with greater number of rules. Further work includes a deeper study for selecting descriptors with a range of values and augmenting them to grammar primitives, as well as a case study with a larger grammar with greater number of rules. The study presented in this paper made use of set grammars that employ atomic primitive elements and limits emergent shapes. It is conceded that an ideal system would allow the development of emergent shapes and have a method that supports their description.

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Parametricism

Indian social need in complexity and chaos

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Abstract. Indian society living in its physical context and administrative boundaries is complex. The contemporary built environment imitating perceived advance technology where development is purely measured by material consumption is chaos. The present approach to meet dynamic and diverse demands emerging from the complexity and economical boom is fragmented and superficial. The challenge is to find order – the hidden patterns - through an approach that analysis and interprets the complexity with the holistic vision to offer contextual variety inclusive of qualitative richness in the existing chaos. Considering that Parametricism is based on algorithms and mathematics it is generally understood as quantification where as it is also important to understand its qualitative impact. The paper is an inquiry on qualitative gains of Parametricism that helps shaping society in Indian context. This is demonstrated by bringing forward understanding on qualitative gains of Parametricism exemplified with an academic exploration and interrelating them with Indian examples to showcase the opportunities.

Keywords. Parametricism; complexity; chaos.

1. Introduction

India is one of the most dynamic countries in the world. It is the second most populous country with 1.2 billion people making it the biggest democratic nation. It is a pluralistic, multilingual and multiethnic society. To create a built environment for 1.2 billion people in such a diverse context involves numerous parameters like individual's life style, cultural background, social requirements, geographical conditions, etc. all of whom live in a hierarchy of economical, political and administrative boundaries, referred to as *complexity.*

As it is true for any society, economy plays a major role in changing the level of complexity. During the last decade of the 20th century India has gone through a major economic transition becoming one of the fastest growing countries in the world. However, despite great economic growth, there are several challenges such as poverty, illiteracy, corruption and inadequate public health care in the society. Economic boom and information technology have given rise to dynamic and diverse demands that ranges from the basic need of housing and infrastructure to the most sophisticated technology dependent and iconic built environments. India has become one of the biggest consumer markets where there is huge dumping of goods with no connection between demand and supply. At times the gap is also because of individual's (designer/developer) beliefs and interests. The only motto is 'To Sell' by means of packaging and marketing which has resulted an arbitrary conglomeration of images, ideas, perceived advance technology, design elements, materials and so on to attract people. The development is measured purely by material consumption and expressed as imitation of form and style rather than true understanding of methods, tools and relevant issues offered by advanced technology. This scenario is referred to as *chaos*. Benefits of economical growth and technology has not translated into any quality services, availability of housing for the under privileged mass of rural population, to resolve issues of administration and policy making for urban development. There is loss of quality and experimentation that supports simultaneity of diverse demands, appropriateness of technology to offer variety and distribute the benefits amongst the society. The challenge is to question the present scenario.

Architecture in India has evolved over centuries beginning from Vernacular followed by Colonisation to Modernism and Post-modernism. Contemporary Indian architecture is going through the era of *information revolution*. The question is how to break this fake imagery of attractive packaged products, specific beliefs and develop a deep understanding of logic and reasoning to create homogenous heterogeneity for Indian society? How to couple the cumulative wisdom of traditional architecture with present demands of the information era? The search is to find an approach that analyses and interprets the complexity with a holistic vision and offers contextual variety having qualitative richness. To find an inclusive approach that offers a framework which keeps all the concise information yet flexible, adaptive and responsive to the changing socio-economic demands and its consequences to offer quality living environment? Some of the methods that have emerged from the technological revolution, if contextualised and understood for their content, may be able to suggest directions. The paper inquires in the qualitative gains of Parametricism to answer these questions.

2. Parametricism - qualitative gain

Parametricism is now a fully mature approach based on inclusive principles and the concept of differentiating fields. Aesthetic and performative gains of Parametricism are accepted and appreciated worldwide where as in India it is still in its infancy. For example, SOM (2010) explored parametrics to derive visual continuity/discontinuity through the external envelope of The Park Hotel, Hyderabad. It was achieved by creating a gradient of perforation and embossing in metal sheets using a digital fabrication technique which revived *'jali'* of traditional architecture. Other demonstrated by Centre for Sustainable Environment and Energy (CSEE) of India is the first zero energy building. Based on parametricism, CSEE also made critical evaluations of the impact of the energy conservation building code of India on commercial building through energy simulation models in five different Indian cities with different climatic conditions.

Beyond aesthetics and performance, as explained by Patrik Schumacher, Parametricism can recognise, measure and simulate the complex patterns similar to Complexity theory and Frei Otto's research. It helps analysing and appreciating the underlying logic and rationality and regenerate the seemingly chaotic patterns. Not only that, it also allows urban environments to reconfigure in different time scales through real-time simulations and visualisations. These abilities make it a powerful tool to analyse, interpret and represent the complexity, while also offering opportunity to observe changing conditions in 3-dimension.

Parametricism is valid at all scales, macro to micro, which means urban design, urban planning and policy making to architecture, interior design and product design. However its strength is directly related to the scale as it resolves complex issues more efficiently since "It aims at maximum emphasis on continuous differentiation, visual amplification of differentiated logics and aesthetic elegance of ordered complexity." (Schumacher 2009, pp 14–24). These methods to find most appropriate solutions are similar to the processes in nature. Its associated system of correlation allows necessary deviation at any particular stage in design process and could use the same to amplify the initial differentiation. It offers a flexible frame work that makes and executes precise and intricate correlations between the whole to parts incorporating performance, aesthetics and qualitative shifts. In an extremely sensitive parametric model when quantitative changes are added to existing parameters such as objects, ambient and observer, it triggers qualitative shifts. These qualitative shifts further offer the possibility to carry forward the idea until the detail articulation." These are the *qualitative gains* of Parametricism which has the ability to transform built environment and society.

3. Tested cases based on parametricism

3.1. B_MOTION: THE LIVING BRIDGE, GRONINGEN

B_motion-the living bridge, the urban extenstion of Groningen, The Netherlands, demonstrate an associated system of correlations that allows deviations and intricate correlation between whole to parts building morphology at all levels where qualitative shifts are carried forward to detail articulation. To perform this, the author and team applied parametrics to analyse the data collected from the site and used them to find urban solutions and form generation. The data collected from site (Figure 1) was used it to create an urban field and establish system of static and dynamic attractos/reppelors in the emergent vector field for multiagent system (MAS) simulation done in Virtools 4.3. The data consisted of population per household, age group, employed/unemployed/students percentage, number of vehicles owned per household, number of boats passing per minutes through the canal. Two simulations at macro and micro level were run based on origin-destination route search and self-organisation principle respectively. The agents reacted positively or negatively from the static an dynamic attractors and repellents based on values assigned for its potentials. Results of simulations were then linked to the related functions.

These determined the pedestrian and bicycle connection between the city and the site (macro) and programmatic requirements and its distribution on site (micro) in the form of point-cloud (Figure 2).

First attempts to transalate point-cloud to geometry involved association of a specific stage of kelidocyclus module and its scaling depending on the distance between points (agents). This failed because it created extremely complex junctions and an overall unstable structure. Therefore a second strategy was applied over the selected area. Functional and structural requirements guided the algorithms to itterate simulation for further refinement. This demonstatrates the the flexibility and adaptability of approach in case of failure.

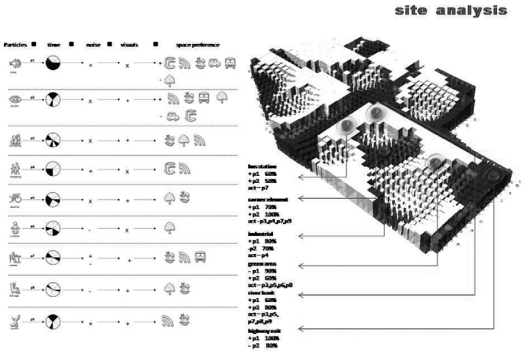

Figure 1. 3D diagram: data representation

A frame system enhanced with two frames and two connecting elements made a fully functional and structurally stable component, thus creating a vertebrae tubular system with structural integrity. The association of analised data to final outcome is maintained by environment responsive structure through openings towards light and visual potentials and wall thickness towards noise level. The same component has been translated to generate towers, gradually changing the functions between walls, floors and ceilings (Figure 3). The construction possibility was tested through a scale prototype based on folding principle which turned out to be extremely stable leading to the manufacturing opportunitiy in sheet material.

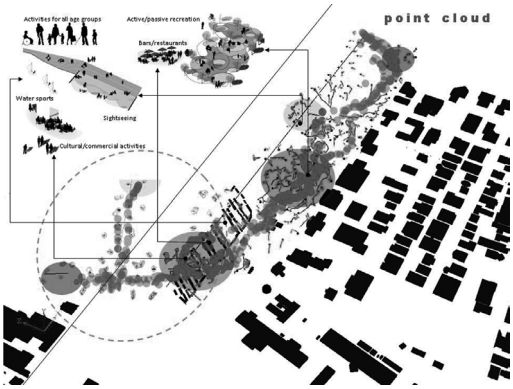

Figure 2. Point-cloud

4. Indian context

To present the entire range of demands today would require a compilation of book size; therefore the paper brings forward some examples that have a sensitive approach towards society and immense potential which can be further explored through Parametricism. These examples recognise, appreciate and implement the qualitative aspects with respect to chaos.

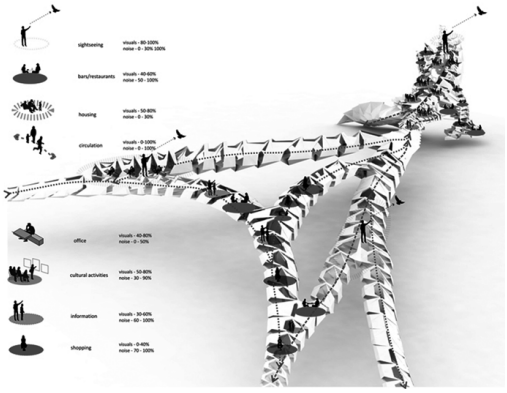

Figure 3. Architectural proposal (final form)

4.1. HOUSING

Gandhi-nu-gam (Gandhi's village), Ludiya, Kutch redevelopment of villages provided housing, social structure, economic restructuring, amenities and facilities provision as well as resource management through participatory process involving people and community. The aim was to retain the livelihood, craft and local architecture which is the identity of the place.

A simulation kit made of Styrofoam board and cardboard was used for interaction between designer and community. The primary design was based on site features, access, orientation and programmatic requirements as understood from surveys (Figure 4). Users reorganised their plots on the simulation kit and were allowed to change as per their choices of location on site, neighbours, and clusters based on kinship and customs (Figure 5). A new layout was then made by the architect based on user feedback, incorporating consideration for climate, open space distribution and scales of neighbourhood. The simulation kit was once again taken to the site and plots pegged for the villager's understanding and available space. After this on site exercise, each villager was allowed their preferred location, neighbours and arrangement of *bhungas* (local house forms) on plots; from this point on the layout was frozen. This finalised arrangement was then translated to working drawings ready for construction. Construction of each unit was done by the owner and his family which resulted in a variety and richness of expression in terms of culture and lifestyle, most suitable construction material and technique for its context.

Figure 4. Primary Design

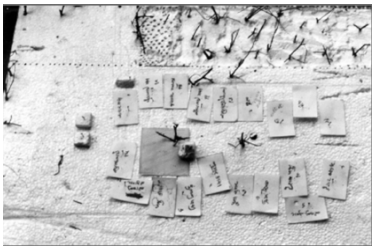

Figure 5. Primary Design end user inputs

Replacing the Styrofoam board simulation kit with computational simulation would have allowed visualising the changes made 3-dimentionally which is stronger and faster communication experience. It would also restrict those changes which try to overrule the basic consideration of climate, open space distribution and scale of neighbourhood which were incorporated later by the designer. These restrictions in real-time would communicate the reasons to the end user. The simulation results could be directly transferred to the design proposal and construction drawings without any time and information gap in the interactive process.

4.2. INFRASTRUCTURE DEVELOPMENT

Bus Rapid Transit System (BRTS), Ahmedabad implemented in the last decade is one of the successful examples of transportation planning. The BRT cell at the Center for Environment Planning and Technology (CEPT),

Ahmedabad, developed a unique approach for urban transport (Figure 6). It used alternate analysis. Critical input for the process included primary data such as Social/urban, physical, existing infrastructure and demand assessment using surveys (mostly household), Google maps and GIS images, photographs and videos. Origin-destination patterns were established based on primary input through alternate analysis. Alternate analysis used specialised software (Emme 3) that provides various alternatives. These alternatives were tested by logical deductive methods. A final choice of route was still based on ground condition, intuition and certain amount of risk. Design work such as road design, junction design and pavement design abased on physical data was then done for the proposed route.

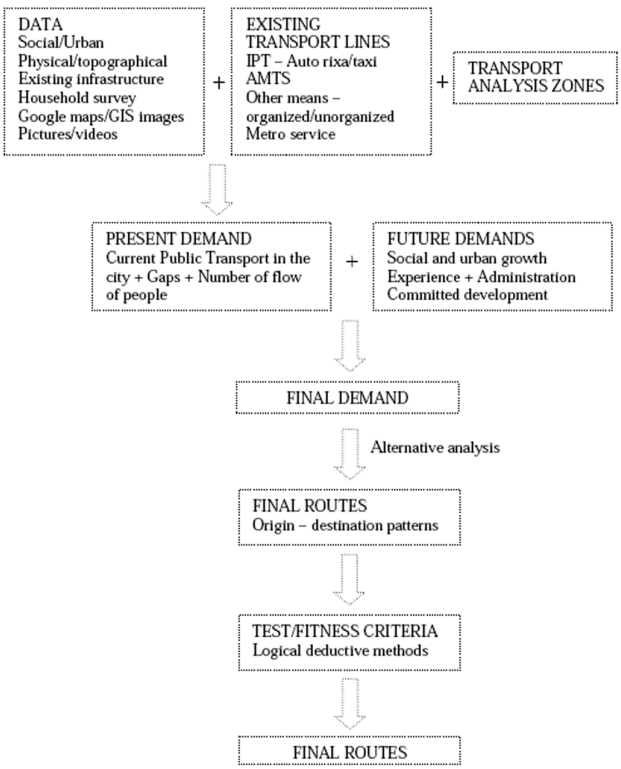

Figure 6. Design process BRTS, Ahmedabad using Emme 3 (Transport modelling engine).

The state/government got involved at implementation stage as the client. The plan/design were not necessarily followed exactly same as proposal. Many

modifications were required due to site conditions and in the public domain; changes were also made due to political/ external pressure. To cater several unknown parameters throughout the process, the project was normally over-estimated whereas in case of any failure, team had to start all over again. In the end solutions were provided that had acceptability for a wide range of stakeholders.

The team already uses vast amount of digital information to be processed in special software. However, this primary data is generated in ways that takes a lot of energy, time and resources. A detailed contextual inventory including physical, topographical, cultural, social, urban and infrastructure can be produced separately as done by GIS Factory for Rajkot municipal corporation, India and shall be provided to all kinds of design and development works. Topographical information consisted of GIS maps plus super imposed total station surveys to correct GIS map errors which produced exact information at 5 meter grid density and contour survey of the terrain at every 50 cm level difference. Urban data included demarcation of plots, its subdivision (if any as property rights), exact building foot print, number of floors defining the owner, 3-dimensional land-use through extensive photography of each property showing the present use. Social surveys recorded population count, occupation, number of working members of the family and general life style. The existing Infrastructure was also recorded. Entire trunk lines below ground including sewage, rainwater drain and water supply pipe with detailed dimensions of pipes, slopes, junctions and location of man holes were marked precisely. Telecommunication lines, lamp post with detail indexing and street furniture added to this information plus entire road cross-section marking paved/unpaved areas, its material specification, location of trees and other physical objects. Such systematic and accurate data bases are more reliable and easy to update by feeding additional information of a new proposal or any changes in the existing scenario. Such detail updated inventory would be useful for accountability and estimation reducing the number of unknown parameters related to an existing scenario. The future demands, the input for final demand calculation, mostly depend on personal opinion of designer and local authority. This can be rationalised through parametric tools and accurate numbers can be speculated for final route search. It would also help finding/ updating alternate routes with respect to the update of the database. Parametricism offers a systematically defined process where each step is traceable so that in case of failure, problems can be fixed at necessary stage and one does not have to start from scratch, as shown in B_motion- the Living Bridge project.

4.3. POLICY MAKING AND ADMINISTRATION

When it comes to master planning and urban design projects, Parametricism involves operation in hierarchy of economical, political and administrative boundaries. In that case it positively helps in policy making and reforming building by-laws. For example, building by-laws of Ahmedabad control all three parameters for building volume – ground cover (45%), FSI and number of floors (four) for low-rise buildings, which results in nothing but boxes of buildings with stilt parking all over the city. Building volume control resulting from computation of individual parameter would give designers the opportunity to create better living condition. Another example here is law regarding balconies being recently changed. They are not free of FSI and not allowed at floor level. This has left no opportunity for people to come out of buildings, which is the life-style due to climatic reasons. It also resulted in less protected openings having only sixty centimetres weather sheds. Rather, these decisions should be made based on the analysis of weather simulations which will not give specific solutions by differentiating zones taking into account exact location and its climatic conditions.

The detail inventory inclusive of intense information help the local corporation firstly to generate revenue, in case of Rajkot five lacs unaccounted properties, which are now registered and fall under property tax laws. Secondly the system is absolutely transparent and accessible between the government and the people.

All such information models when linked at city or national level, one can also analyse and interpret urban flux and patterns for optimum use of scarce resources and its management. The use of Parametricism will lead to adherence to the by-laws without compromising with the qualitative requirements of the built environment.

5. Conclusion

Integrating this cumulative wisdom and intelligence of computational tools can evolve into holistic wisdom inclusive of quality, aesthetic and performative gains to coexist in present and future Indian complexity and chaos in more rational and prudent way. This is precisely the *gain* of Parametricism – the need - in Indian complexity and chaos. The explorations show that the deep understanding and application of Parametricism helps distributing economic and technological advancements at social level. This cumulative intelligence helps in organising and incorporating vast amount of data that is variable and hence left out of purview of designer's considerations. It can precisely find the demands such as housing, infrastructure development and so on. For mass

housing, simulations make better participatory experience leading to acceptance of social variables as parameters of design. It formulates programmatic requirements, its distribution on site and continuous differentiation leading to build form variation and enhancement from macro to micro level. In case of transport planning, it is effective at alternate route search using complete updated scenario in real time and makes rational choices reducing risk factor, controls cost overrun by reducing unknown parameters and access to necessary stage in case of failure. And it is effective for administration and policy making at master planning and urban design guidelines which aims public health and development. It also helps reforming policies/building-by-laws.

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5B PRACTISE-BASED AND INTERDISCIPLINARY DESIGN II

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A SUPPORT SYSTEM FOR INTEGRATING SMART TECHNOLOGIES INTO EXISTING BUILDINGS

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Abstract. We propose a support system for infill elements that integrate smart technologies based on Open Building principles. The design requirements were collected from design practitioners. It consists of an architectural sub-system and an information sub-system. A working prototype was constructed and some smart infill components were implemented to demonstrate and examine the system design. The prototype was evaluated by design practitioners.

Keywords. Support system; smart house; open building; building renovation.

1. Introduction

Integrating smart technologies into existing houses generally requires major renovations, which maybe as time-consuming and/or costly as building a new house. Given that a building may last for decades, the needs to allow incremental integrations of smart technologies into buildings out-weight that of new smart houses. Open Building provides a systematic approach towards the construction of buildings (Habraken 1972). Two key concepts of Open Building are supports and infill. Supports contain all permanent, shared building services. An infill system is a carefully pre-packaged, integrated set of products, custom prefabricated off-site for a given dwelling. By decomposing the construction of a building into various components that can be assembled through building products, the process enables incremental modifications and improvements of existing buildings.

We propose a support system for infill elements that integrate smart technologies. Noting that residential buildings are the largest building stock to be improved with new technologies in many Asian countries, the system is

designed for the interior environment. That is, the system provides support for interior partitions of spaces while the system itself is an infill of the overall building structural support system.

2. Supports and infills

Habraken (1972) introduced the principles of Open Building that divide a building in two levels: support and infill. This provides a systematic ways of relating building elements and enables variations or customisation according to residents' needs. The two levels are also levels of decision-making where residents can decide what infills are needed and where infills should be placed. To realise Open Building, Habraken and Van Randen developed the Matura infill system (Kendall 1996, Kendall and Teicher 2000, pp. 67-168). The Matura infill system is made of two elements: the Matrix Tile and the Baseboard Profile. The Matrix Tile system is based on a 10 cm by 20 cm grid that accounts for the positioning of each component and its relationship to other elements. The Baseboard Profile is a track component that serves as the base for interior partitions. These components provide adaptability in design, fast on-site installation and future changeability.

The curtain-wall construction of building facade is one of the first innovations that allow wall panels, infill elements, to be manufactured separately from the building structural framework, a support system. Examples, such as the "Blinkenlights" project in Berlin, the "BIX" façade of Kunsthaus of Graz, and the "SPOT" in Berlin's Potsdamer Platz (Hall 2006), are pioneering works of integrating smart technologies into the infill elements, i.e. curtain-wall panels. To facilitate such a kind of infill elements, the support system provides not only structural backing but also power supply and information communication. Furthermore, a building may contain various types of smart infill elements, as we have developed previously (Chien 2009), the support system should provide flexibility to allow various types of infill as well.

3. System design

Integrating smart technologies into the living environment has been a topic of research since late 1990s. Projects such as Neural network house (Mozer 1998), Aware Home (Kidd et al. 1999) and EasyLiving (Shafer et al. 1998) has constructed prototype or demonstrative houses. To operate these houses, one needs to be able to afford the maintenance and to know smart technologies well. As smart technologies become affordable to general public, architects and interior designers are getting frequent requests from their clients to integrate smart technologies, for instance smart indoor environmental controls or smart lighting controls, when remodelling houses. We aim to develop an infill

system that may assist architects and interior designers to design and deploy smart technologies for their clients.

3.1. REQUIREMENTS ANALYSIS

To understand the requirements of such kinds of system, we interviewed three design practitioners, one architect and two interior designers, to collect possible kinds of infill elements or functional supports for interior partitioning walls. A set of keywords regarding activities, spaces, and interior elements (e.g., fixtures, furniture, appliances) are extracted from interviewed data. A researcher then worked with each design practitioner to analyse the relationships between these keywords with the affinity diagramming method (Beyer and Holtzblatt 1998; Figure 1). Resulting affinity diagrams were consolidated into a relationship table of spaces and interior elements, which in turn sets the functional requirements of our support system.

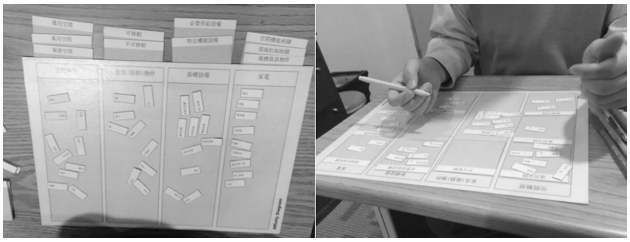

Figure 1. Affinity diagramming analysis.

Our design practitioners identified three types of space in a house: common space, designated space and service space. The common space is used by all members in a house; it includes living room, dining room and drawing room. The designated space includes kitchen, study room and bedroom; they are mostly private spaces used by specific members for designated functions. The service space includes entrance hall, corridor, balcony and bathroom. For the non-movable furniture and building elements (Table 1, last three rows), cabinets are needed in all spaces. For movable furniture (Table 1, first six rows), folding screen (a free-standing partition) may be needed in living room, dining room and entrance hall. Service equipments and infrastructure include kitchen equipment, bathroom equipment, security, electricity, lighting, plumbing, and information equipment. Security and information equipments are needed in almost all spaces (Table 2). Appliances commonly used at home are those for communication, designated purpose, environmental control, and information and media. Communication appliances, such as telephone set, are needed in almost all spaces. Designated purpose appliances are required in specific spaces. Among three environmental control appliances, lamp (movable light-

ing) is desirable in all spaces. For information and media appliances, display screen is considered in balcony (Table 3).

TABLE 1. Association between furniture, building elements and spaces.
(• strong association; ⊙ mild association; ○ weak association; others, no associations)

	Common space			Designated space			Service space			
	Living room	Drawing room	Dining room	Kitchen	Study room	Bedroom	Entrance hall	Corridor	Balcony	Bath room
Chair	⊙	○	•		•		○			
Table	⊙	⊙	•		•		○			
Bed						•				
Sofa	•	•	○		⊙				○	
Folding screen	⊙		○				○			
Window Curtain	○	○	○		⊙					
Cabinet	⊙	⊙	⊙	⊙	•	⊙	⊙	⊙	○	○
Door	⊙	○	○	○	○	•	⊙	○	⊙	○
Window	•	•	○	•	⊙	•			⊙	•

TABLE 2. Association between service equipment, infrastructure and spaces.
(• strong association; ⊙ mild association; ○ weak association; others, no associations)

	Common space			Designated space			Service space			
	Living room	Drawing room	Dining room	Kitchen	Study room	Bedroom	Entrance hall	Corridor	Balcony	Bath room
Kitchen equipment			○	•						
Bathroom equipment	○									•
Security equipment	○	○	○	⊙		○	⊙		○	○
Electricity	⊙	⊙	⊙	⊙	⊙	○	⊙	⊙	⊙	⊙
Lighting	⊙	⊙	•	⊙	•	•	⊙	⊙	⊙	•
Plumbing			○	•					•	•
Information equipment	⊙	⊙	○	⊙	•	○	⊙		○	○

TABLE 3. Association between appliances and spaces.
(• strong association; ⊙ mild association; ○ weak association; others, no associations)

	Common space			Designated space			Service space			
	Living room	Drawing room	Dining room	Kitchen	Study room	Bedroom	Entrance hall	Corridor	Balcony	Bath room
Telephone	•	•	○		⊙	○	○	○	○	○
Cell phone				○	⊙					
Refrigerator			⊙	•						
Oven			⊙	•						
Washer									•	○
Fan	○	⊙	○		○					
AC	⊙	⊙	⊙	⊙	•	⊙			○	
Lamp	⊙	⊙	⊙	○	⊙	⊙	○	⊙	○	○
Display screen	⊙	•			⊙		⊙		○	○
Audio set	•	⊙	○	○	•	○				
PC	⊙	○			•		○			

Taking these associations into account, we defined vertical infill zones into three parts (Figure 2). Zone A takes up the space of 240-cm and higher; it is beyond the standing reach of hands. It is suitable for infills of environmental control appliances, such as AC unit and lighting. Zone B is between 100-cm and 220-cm; it is the primary zone where living activities take place. The suitable infills are cabinets, utility supplies (for instance electric outlets, faucets) and working surfaces. Zone C is below 70-cm; it is easily reachable while sitting. The suitable infills are low cabinets and utility supplies (such as network outlets). Between any two zones, buffer zones are provided to allow for adjustments. These vertical infill zones are the basic references for the design of our infill system.

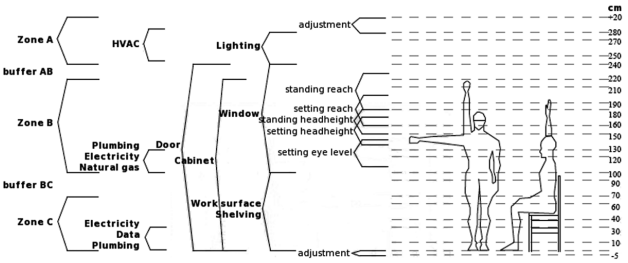

Figure 2. Vertical infill zones.

3.2. ARCHITECTURAL SYSTEM

To provide the structural support, our support system is based on a 30 cm modular grid (Figure 3). Each key supporting column is 10 cm wide and contains 5cm interface strips to connect to infill elements. The smallest clearance between two columns is 20 cm, however, a more feasible clearance between two columns is 50 cm. The electricity and information communication supports are provided utilising the hollow in each column. The system connects to the existing building elements, floors, ceilings and walls, with interface components.

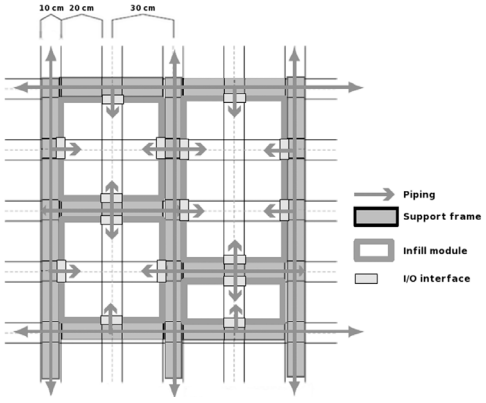

Figure 3. Modular grid of architectural system.

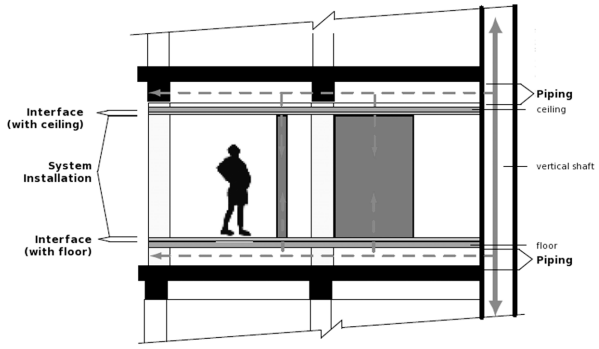

Figure 4. The system in relation to existing building elements.

3.3. INFORMATION SYSTEM

To support infill components with smart technologies, information communication is essential in the support system. With the architectural system providing hardware support for electricity and data network connection, we envisage our information system as a network of agents. The "Smart House Control System" is a special agent that is responsible for the overall information interface of the house. It maintains the list of all "Smart Infill Component" agents and can relay information to each agent (Figure 5). Each "Smart Infill Component" is an agent that can connect to other agent but operates autonomously with its own rules of interaction, sensors and actuators. Members of the house should be able to interact with any agent directly through handheld devices, such as a smart phone. All data with this information system should be stored in a central database.

The communication protocols between the "Smart House Control System" and "Smart Infill Component" agents, ideally, should support all existing standards of smart home network that are proprietary (e.g., INSTEON® by SmartLabs, Inc. and LonWorks® by Echelon Corporation) or open (e.g., X-10 and KNX (EN 50090, ISO/IEC 14543)). In this research, we have assumed that "translations between different protocols" to be provided by another party and the service(s) may be integrated into the "Smart House Control System" or the "I/O interface" component of the architectural support system (Figure 3). Our research team has been conducting studies on various configurations of the "Smart House Control System" agent and the "Smart Infill Component" agents. The "Smart House Control System" can be a special agent that organises "Smart Infill Component" agents of the same type into a Cellular Automata network to implement rules of interaction among agents (Huang and Chien 2008, 2009). However, given that the appropriateness of configurations and

the rules of interaction depend on the actual installations of infill components, we decide to keep the information system as simple as possible.

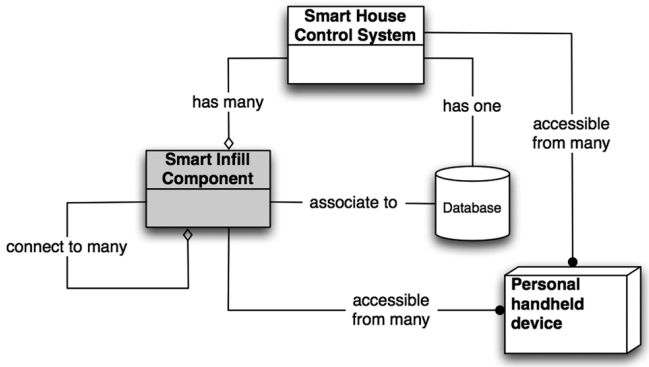

Figure 5. Information system object model.

4. Prototype and evaluation

We have constructed a functional prototype to demonstrate the feasibility of our support system and some possibilities of smart infill elements. The prototype is a partitioning wall of 210 cm high and 120 cm wide (Figure 6). To demonstrate the electricity and information communication supports, we have tested an information display infill that shows occupancy status in the environment. To demonstrate the support of kinetic infill elements, an adjustable (protruding) lighting infill is tested. In addition, to demonstrate the support of interaction between occupants and infill elements, the adjustable lighting infill is designed so that the light intensity level is adjusted according to the ambient lighting conditions.

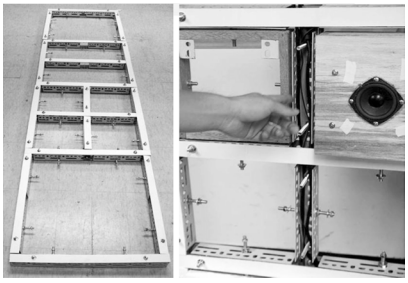

Figure 6. Support and infill prototypes.

To validate the system, we conducted another round of studies with design practitioners. We invited one of the three practitioners participated in the previ-

ous interviews and asked him to complete an interior design using our system. The other two practitioners were provided with documentation showing capabilities of our system and asked to speculate possible uses of the system and the use scenarios. The results shown that design practitioners were able to use the support system for partitioning spaces and positioning various infill functions. However, since they knew very few smart household products, their use scenarios contained little utilisation of smart technologies.

5. Discussion

We proposed a support system to integrate smart technologies into existing buildings. For designers, it is a design support with dimension, position and interface through modular coordination. We built a working prototype to demonstrate the possible implementations of the architectural elements as well as smart infill components. The smart infill components were implemented as independent agents that interact with the user control and the environment. However, they did not interact with each other. We have not implemented other parts of the information system, namely the "smart house control system" and the database.

Our purpose of developing the support system is not in promoting technology but in supporting the integration of new technology, should there be a need. Intille (2006) argued that the goal of investigating smart house is to make people smarter. We think alone the same line. Furthermore, we believe the essence of "smart" is "being right". We are investigating on "right technology" for people in need. We do acknowledge that sometimes "right technology" means "no technologies".

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JUST IN TIME DESIGN

Developing parametric design tools for architectural design

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Abstract. In this paper we will present custom design and parametric programming strategies for the design of complex spatial structures based on our applied research for a 10.000 m² freeform technology centre in Düzce, Turkey. The goal is to develop intuitive, easy-to-use parametric design components for layout, analysis, optimisation and aesthetic architectural free form design.

Keywords. Parametric design; freeform architecture; quadrilateral meshes; software development; fabrication.

1. Introduction

The ease of freeform modelling in CAAD (Computer Aided Architectural Design) software tools has introduced a wide variety of new forms into architectural design. Even though freeform designs can be perfectly represented in the virtual space, common CAAD tools are not optimized for the actual realisation and fabrication of large scale freeform architecture. Taking on these issues as a business opportunity, specialized geometry and computer science consultants such as designtoproduction or Evolute support architectural offices in optimizing initial designs for fabrication. Even before this new trend, building contractors had developed their own "in house" software tools to solve geometry and fabrication related problems and to break down geometry into machine code, production drawings and mounting plans. However, consulting services and their software tools are exclusive to a number of well- known architects, but not affordable for small scale architectural offices.

In this paper we will briefly discuss the major developments and trends in the last decade and present a first new approach of customized design and

programming strategies for a wide range of architects, based on our applied research for a 10.000 m² freeform design, the Düzce Teknopark, a technology centre for Düzce University in Turkey (Figure 1). The goal of our research and practice is to implement intuitive, easy-to-use digital design tools for layout, analysis, and aesthetic design strategies for architectural freeform structures. We will further discuss how to break down freeform building envelopes into manageable program modules for sharing data with consultants such as structural engineers and building physicists and how to streamline the workflow without having to rely on existing BIM software (Building Information Modelling) such as Digital Project.

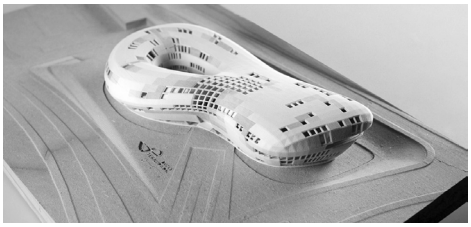

Figure 1. Scale model of Düzce Teknopark (3D-print on CNC-milled site model).

2. Düzce Teknopark

On November 12, 1999, the city of Düzce was shook by the 7.2 magnitude Düzce Earthquake. The remaining architecture is a wild mixture of quick reconstructions following the disaster. In 2002, the University of Düzce was founded to attract young people and has since become one of the main driving forces for future developments in Düzce.

The new building of Düzce Teknopark is situated on a geographic saddle, at the same time overviewed by Düzce University´s rector´s building while having a wide downhill view of the whole Düzce University campus. The fact that the building can be seen from a bird's eye´s view represents a unique situation which requires the "fifth" façade – the roof – to integrate seamlessly in the overall design.

Infinity of science and the convergence of industrial and academic research were the inspiration to develop a multifunctional twisting, three-dimensional loop emerging from a toroidal primitive. The environmentally self-sufficient and self-supporting building envelope will house office spaces and research labs for industry and university spin-offs. Incubating these new technologies and innovations requires highest security standards where each floor has to be encapsulated. In the foyer, the double façade twists like a conch shell into an

overwhelming entrance space, creating a pocket within the double-façade. As an analogy for the fertilisation process, the penetration of the building with researchers, clients, and visitors is articulated in the atmospheric climax of the entrance hall as a meeting area “In-Between” (Figure 2).

Figure 2. Interior view of the entrance hall in between the outer and inner skin.

3. Deep structure – necessity and simplification

The technological challenge of freeform architecture is not just a question of segmenting NURBS or subdivision surface to producible units, but to consider the complete spatial structure of the building, which links the interior to the exterior and vice versa, where data is fed in either from the interior, e.g. according to structural requirements, or from the exterior, e.g. due to material changes of the cladding elements or building physics. However, most current research aims to resolve just the freeform skin to meet structural and production constraints. This results very often in a posteriori solutions where the spatial structure of the inner and outer space alike is already given. (Pottmann et al. 2006, Eigensatz et al. 2010). Other research deals mostly with surface structures and ornaments (Dimcic and Knippers 2011).

In our applied research for Düzce Teknopark we aim to optimize the building not according to a *layered* system e.g. refitting the mesh to floor planes only (Figure 3) - but rather as a parametric, interdependent *3d space structure* considering *micro* (e.g. joint conditions), *macro* (material conditions) and *spatial structures* bounded by 3-dimensional *space edges.* The representation is simplified to points, curves or surfaces to which we consider a *deep structure.* The term deep structure is originally a linguistic expression and refers to a technical construct that seeks to unify several related structures. (Chomsky 1965) *Deep structure* best explains the requirements for a parametric design tool and the necessity of creating predefined *relations* of inner and outer spatial systems which are not an inherent subdivision of space.

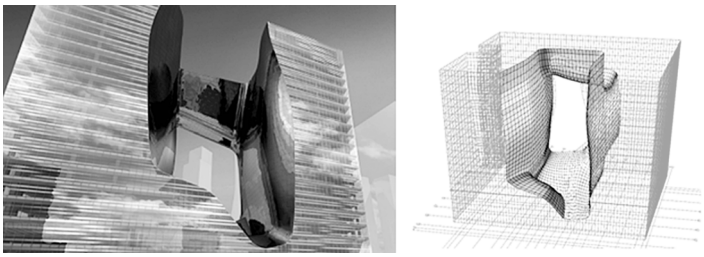

Figure 3. The Opus (image courtesy of Zaha Hadid & Associates) (left), planar quadrilateral mesh refitted to floor slabs (right).

The major constraints of the parametric model are determined by the relation of e.g. environment, structural behaviour, building physics, material and production requirements. Parametric design ensures that flexibility is guaranteed throughout all construction phases, so that unforeseen events can be accommodated. As an example of the importance of flexibility, the 3D data model of the outer skin of Kunsthaus Graz (Cook and Fournier 2003) differed from the realized acrylic glass surface up to 30 cm and had to be manually refitted onsite (Figure 4) compared to a bride who has to be squeezed into her wedding dress before the ceremony due to weight gain. However, when material does not allow such flexibility as acrylic glass, this refitting process has to be performed on the 3D data. *Refitting* is therefore an important constraint that is omnipresent from design to fabrication and needs a lot of attention, analysis and a flexible parametric strategy.

Figure 4. Onsite refitting of acrylic glass panels of Kunsthaus Graz (left), digital NURBS surface (right).

Our research on parametric deep structures and fabrication strategies is a direct result of such onsite experiences. In the following chapters we will explain our strategies for the development of a parametric design tool, that allows architects to increase and decrease information by simply plugging and unplugging separate components for design and tools for analysis.

4. Teknopark parametrics

Subdivision modelling allows the rapid generation of freeform shapes, which can be adaptively subdivided and easily modified even after they've been created, while keeping the continuity of the surface. An alternative modelling concept is NURBS (non-uniform, rational, B-spline) modelling, which mathematically describes iso-parameter value curves or surfaces and therefore offers total accuracy (e.g. for fabrication), while the accuracy of subdivision surfaces depends on the degree of subdivision. By translating the subdivision surface into a NURBS surface for further editing in the CAD software Rhinoceros, we are combining both techniques for Düzce Teknopark and gain the ease of freeform-modelling from subdivision surfaces and the accuracy of NURBS (Figure 5).

Built on top of Rhinoceros is the parametric design plugin Grasshopper which can reference all geometry inside the CAD program and include it in its parametric model. The advantage of Grasshopper compared to scripting, is that changes propagate immediately through its parametric graph and cause the visual preview to refresh, allowing a near-realtime environment where the designer can immediately see the effects of his actions.

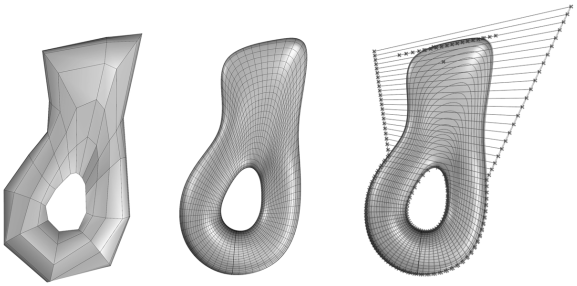

Figure 5. Coarse mesh for subdivision (left), NURBS surface (middle), parametric panelisation in GH (right).

4.1. INTERIOR AND EXTERIOR

As we consider the whole deep-structure of the building, various parameters have to be considered, dynamically changing the thickness of the outer skin, as required by material properties or building physics (Figure 6).

This value has a direct impact onto the available office space, but also on the interior structure. The general typology of the interior support structure was a collaborative effort with the structural engineer, defining simple, struc-

tural rules such as “one concrete column every n meters” with “a maximum angle in x degree according to the tilt of the outer skin”. By parametrising the shape of the support structure as well as its spacing and orientation, we are able to implement a good representation of the final structural members inside, while still allowing rapid changes due to e.g. increased external loads, material changes, or building physics.

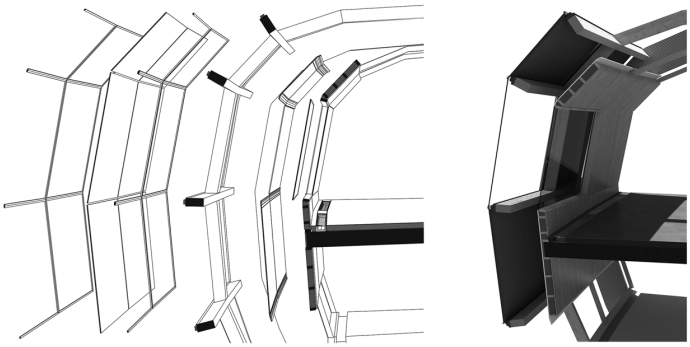

Figure 6. Dynamic depth of the façade structure (left), 3D-section (right).

4.2. REDUCING AND ADDING INFORMATION

Keeping the 3D model in Grasshopper as abstract as possible with a minimum amount of geometry represented by points or curves - unlike the solid representation seen in the 3D-section (Figure 6) - is crucial for the near real-time 3D data processing. Another relevant factor, which we have experienced in our practice are the different tolerances of programmes resulting in a problematic data exchange between different software tools. Most structural engineering software e.g. for finite element analysis needs point accuracy of 0, while many CAD programmes have rather high tolerances, such as Autocad’s default setting of 24 digits or Rhinoceros’ with only 3 digits. A similar problem can be experienced with CNC machines. Exchanging surfaces or solids within different software environments can cause edge discontinuities and unforeseen differences in surface parameterisation or mesh representation. A reduced 3D model concept only representing deep space edges and points is therefore a promising approach. Adding more information to the 3D model can also be automated see Figure 7. Our tools will allow flexible “dress codes” according to various occasions such as structural behaviour, building physics, mechanical engineering etc. incorporating dynamic changes and mitigating “weight loss/weight gain” problems.

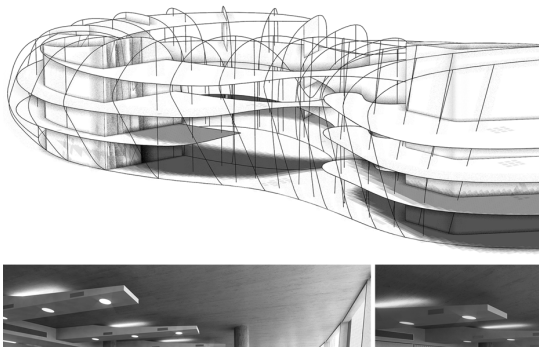

Figure 7. Simplified deep structure of interior space(top),example for results of inner spaces with different amount of information (bottom).

By parametrising the interior of the Teknopark, we receive a maximum of freedom of design when dealing with the outer skin, which has to be considered the cost-driver of the project and the building part with the most financial headroom for optimisation. Therefore, the parametrically gained freedom of design can be translated into tangible optimisations and reductions of costs. Going back to the example of the Opus by Zaha Hadid, the parameterisation and planarisation of the freeform surface enabled a cost saving of 25%, as estimated by the contractor.

4.2. QUADRILATERAL MESHES

In order to create a strategy for quadrilateral meshing of the Duezce Teknopark, it is important to carefully analyze the NURBS surface and its isocurves. We can formulate the initial requirements for a quadrilateral mesh as the following: The primary support structure *must not twist geometrically in space*, it should *be distributed evenly along the building*, leading to *elements of similar size*, and it has to be *aesthetically pleasing*.

In contrast, the secondary structure can follow the isocurves of the toroidal area to profit from the inherent planar segmentation of the geometric primitive. To be able to distribute the quad panels more evenly, the parametric system allows us to dynamically move away from the isocurves in the non-toroidal areas of the loop (Figure 8, left and middle).

4.3. ANALYSIS

Due to the fact that the outer skin is the biggest cost driver of the project, and that small changes to the geometry can have a drastic impact not only

on finances, but also on building physics, structural integrity, and fabrication, various analysis tools are implemented in the parametric definition. The analysis tool with the biggest impact on cost is the planarity visualisation. In the discourse of planarity in architecture, it is important to consider that mathematically absolute planarity with zero tolerance does not exist. All construction elements depending on the material used have certain tolerances, as well as not being mathematically planar in the first place. While allowing the general optimisation of the planarity value, this analysis function also allows us to assign quads to so-called "planarity-groups", which all have a common amount of planarity tolerances. We can therefore aim to e.g. place glass only on panels with a unplanarity of less than 6 mm for glass panes >1.5 × 1.5 m, while areas with higher unplanarity can be assigned with more flexible materials (Figure 8, right).

Further analysis functions measure the uniformity of all panels and output the result as a graph or calculate the angle between the panels' normal vectors and the vectors of sunlight, allowing an approximate estimation of the solar gain on each panel. All these analysis functions can of course be superimposed, so that e.g. only the solar gain of panels with high planarity is evaluated.

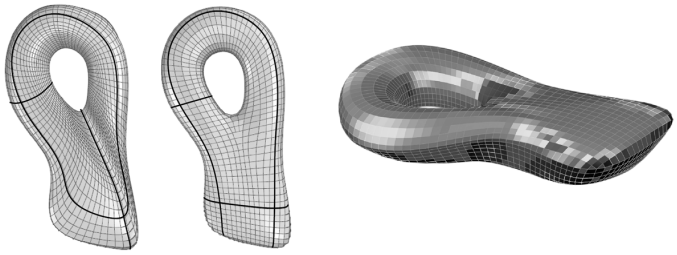

Figure 8. Optimisation and Analysis: Top view before (left) and after (middle) mesh optimisation, planarity analysis (right): blue is within required glass planarity tolerances.

4.4. MODULARITY, ADAPTABILITY AND OPTIMISATION

It is important to consider that the origin of the parametric definition is the initial driving surface, as it was imported from the subdivision modeller. Therefore, whenever the initial surface or design values are altered the definition stays valid as long as the general surface topology stays the same. This allows a new freedom for designers, where all parts can be changed at any time instead of having to lock important input geometries at a certain stage, which can cause problems peaking in the onsite manual refitting of the outer skin layer, seen in projects such as Kunsthaus Graz.

Another relevant aspect is performance and modularity: Grasshopper itself consists of components containing specified functions which are laid out as an acyclic graph. Changes to that graph propagate upwards, meaning that only components where the input data is modified get refreshed. If e.g. changes are performed to the planarity analysis, the other analysis functions do not refresh. In reverse, if the user adjusts the quadrilateral mesh, all analysis functions, the interior, and the support structure have to be recalculated and updated. As this process can take a few seconds, the immediate feedback is no longer given and working with the definition becomes slow and cumbersome. However, due to the modular nature of Grasshopper, it is possible to quickly disconnect ranges of components from the graph, so that only the currently relevant components are calculated (Figure 9). As all relationships between the components are clearly displayed by Grasshopper's graph, the user can quickly judge if disabling a group of components will affect a relevant function. Compared to traditional scripting, Grasshopper's modularity allows a much bigger flexibility and more effective optimisation when working with large parametric setups (Davis et al. 2011).

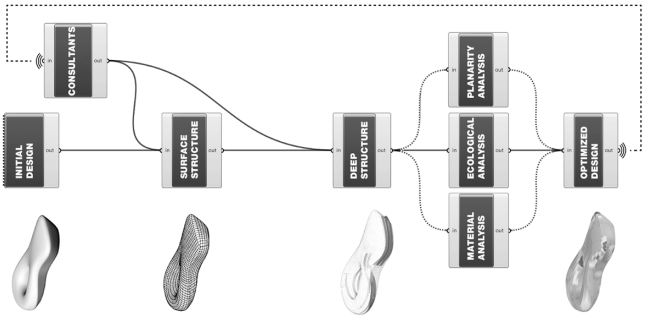

Figure 9. Modular Grasshopper workflow: Plug and unplug components for customized feedback and performance optimisation.

4.5. OUTPUT

This elaborate parametric model not only allows a fluent interaction with the building, but also the automated extraction of e.g. panels and structural members into individual files, and the generation of basic floor plans that clearly show all structural elements and the space edges of the deep structure of the building. Keeping the 3D-model as "slim" as possible is one of the major challenges in a project of such a scale as Düzce Teknopark. Our various "intuitive" design approaches have shown that a slim parametric model

reduces the risk of losing track of information and facilitates reusing existing groups of components.

5. Conclusion and outlook

The flexibility of the digital tools presented in this paper is expected to enable us to quickly implement constraints that we do not know at this stage of design, e.g. the *human scale* onsite, where CAD illiterate workers have to process complex data for mounting and assembling. From our experiences at projects such as Kunsthaus Graz, BMW Munich or Martha Herford and our own projects executed in non EU countries, overloaded construction plans are obstructive onsite

Our tool will follow the question of how to filter the architect´s desire to control all 3D data of all parties simultaneously on the one hand and how to easily break down 3D data according to the needs of all involved parties and the building site on the other hand. We refer to this software development strategy as *Just in Time Design*, where parametric schemata are developed in small portions "on the fly" and expanded, adapted, plugged and unplugged for the following design phases.

Inhouse customised tools allow small architecture firms to convince clients of their technological capabilities: Freeform architecture therefore does not have to be the sole property of the big players anymore.

Acknowledgements

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RESPONSIVE ARCHITECTURAL SURFACE DESIGN FROM NONLINEAR SYSTEMS BIOLOGY

Responsive architectural design by computational methods

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Abstract. The fundamental processes in living systems can be a potential resource to derive nonlinear relationships that could find application in the design of responsive surface from an architectural standpoint. This research focuses on deriving a parametric relationship from a phenomenon in cell biology to generate an architectural expression of responsive surface/ façade. It further delineates the dynamic feedback mechanism from the environment and user as control factors. Through extensive investigation of cell-to-cell connections in the mammary epithelial cells and review of evident relay of communication across the entire system of cells, we could unfold the logical parameters of the biological system. Parametric modelling indicating the causality of the surface condition, changes with the change in extracellular matrix. This gives an opportunity to manoeuvre the surface parameters, contrary to the involuntary cell environment where the behaviours are under the control of a physiological process. Architecturally, the dynamic relationship of surface in a hybridised model, explains that interactivity is not a mere one to one response to a stimulus. Evidently, this interactive process can be a sophisticated loop of feedback through different materiality and componentry that play their effects (and are played back) by "active" surfaces.

Keywords. Computational design; responsive architecture; sustainable façade design; bio-inspired design; bio-mimicry**.**

1. Introduction

1.1. BIOLOGICAL CELL SYSTEM RESEARCH

The intent of biological research section is to investigate the relay of communication across the system of epithelial tissues made up of smallest epithelial cells.

The Epithelial cell membrane is visualised as an active conveyor of changes, when the complex procedure of cellular transmission occurs. We are interested in the dynamic relationship between the cytoskeleton and extra cellular matrix (ECM) that occurs through the interface of the epithelial cell membrane. The cytoskeleton reconfigures when changes occur in the cell membrane and vice versa. The vision that the cells within the tissues functions as an integral unit in architecture comprising their adjacent micro environment was strengthened from the views of cell biologist Paul Weiss in 1945 (Sabin and Jones 2008). He quoted "the living units enmeshed in the microenvironment (that includes extracellular matrix ECM) binds them to the substratum" (Weiss 1945). Mina Bissell, refined this idea to suggest that a state of "A dynamic reciprocity exists between the extracellular matrix on the one hand and the cytoskeleton and the nuclear matrix on the other hand" (Bissell et al. 1982). Conrad Wellington's epigenetic landscape's abstract machine is used to understand the dynamical system tied by relations that echo throughout. If we suppose that some of the 'pegs' in Waddington's model are environmental factors, rather than genetic loci, it can be manifested that deviations in these environmental vectors are relayed to the surface that acts as an active interface to demonstrate the changes in the environment (Goldberg et al. 2007) (refer Figure 1).

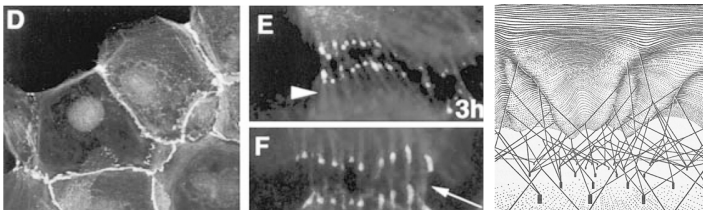

Figure 1. Shows formation of adhesion junctions between epithelial cells. The image on the extreme right shows Wellington's epigenetic model.

In order to model the biological system parameters, we studied specifically the interaction of human mammary epithelial cells with the extracellular matrix components, laminin, tenascin-C and E-cadherin. Normal cells rest on a layer of laminin, and the cells surrounding breast cells produce tenascin-C. Tenascin-C actively promotes tumour formation. The effects of change in the configuration of cells from an orderly state to that of disordered disruption, is that of cancer. The Epithelial cells maintain physical contact with their neighbours through a combination of adherens junctions, gap junctions, tight junctions and desmosomes. Adherens junctions are connections between adjacent epithelial cells. These are anchored to the cytoskeleton of the cells. E-cadherin is the most prominent element present in the ECM that helps to create these

junctions. The presence of tenascin-C indicates, decreased E-cadherin function that can lead to tumour growth (Vasioukhin et al. 2000, Herber et al. 2008, Sabin and Jones 2008).

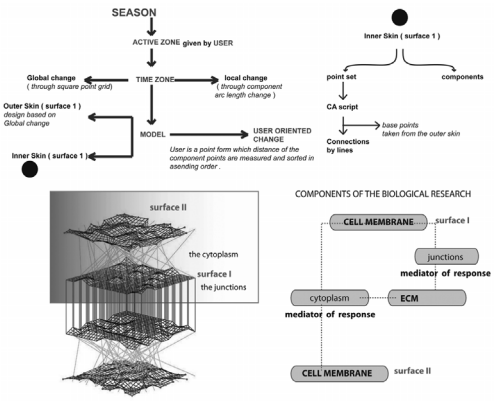

Figure 2. Flowchart on top shows the pseudo code of the framework. The flowchart on the bottom explains the basic algorithm derived from the bioresearch of epithelial cell systems.

Change in the tenascin-C content of ECM changes the adherence junction properties that reconfigure the cell surface and cytoplasm. Cytoskeleton here acts a medium to transfer response to the cell surface form the adherens junctions. The interface of change is the cell-surface/cell membrane and the initiator of this change is the ECM, while the medium of transmission being the junctions and cytoplasm. Presence of tenascin-C or state of decreased E-cadherin induces the disorganised state of the tissue cells thus acts as the cause of disruption of organised cell-to-cell array and their relationship to the ECM (Vasioukhin et al. 2000, Herber et al. 2008, Sabin and Jones 2008). Consequently, tenascin-C is being used as a control parameter of study in this research. The cells manoeuvre from the orderly configuration to a disorderly state by tenascin-C and back to the phenotypical expression of orderly behaviour in the absence of tenascin-C. We decided to focus on cell-to-cell connections for the sake of the clarity in the study of relationships, which will further help us to map the biological process with a greater degree of precision.

Architecturally, the dynamic relationship of surface in a hybridised model, presents a refined environment in which different material component can affect the degree and magnitude of transmission of dynamic behaviour. In an abstract view, architectural elements through their composite complex systems might become more like cells, able to transmit information attenuated or intensified by their materiality. The computational model shares same level of complexity and constraints as that of the biological system of cell-to-

cell interaction. We drew an analogy between the proposed responsive surface design framework and the cell system research based on logical as well as intuitive parameters. The cell membrane is considered the active responsive surface, the tenascin-C and E-cadherin parameters in ECM model are considered environmental factors affecting changes, the cytoskeleton reflex complied with the user-end control parameters and adherens junctions and desmosomes are visualised as tubular steel connections between the two layers of responsive surface.

1.2. PRELIMINARY COMPUTATIONAL FRAMEWORK

The concept of responsive architectural surface and 3-dimensional space has been duly adapted from the biological research of ECM cell-to-cell connections, as it has been cited in the previous section. The complex computational model has been framed in Bentley's Generative Components parametric software. A surface embedded with smart components on 4-point grid base, is modelled on the four sides of the space/room to be tested against both external and internal environmental parameters. External factors considered are wind, day lighting and humidity conditions of the room , while the internal factors specifically focused on occupancy, time phase and user location. Two back-to-back surfaces are modelled (on each of the four sides of the room) with a cavity in between to negotiate both external and internal environmental changes respectively (refer Figure 6). The research strongly focuses on the responsive qualities of the building skin to understand, how it adjusts itself with the immediate environment like sun angle, air-quality, wind direction & occupancy. The research intent is to develop the external and internal framework of the façade module of a few story building. The walls or surfaces are formed of smart components whose mutual interaction is designed in a fashion, which imparts response to the internal and external environment. It comprises of some kinetic components similar in nature to Topotransegrity structures along with a generic responsive structural system, which adapts to isolated spatial requirements. It is capable of various transformations, which range from small-scale surface articulations to large surface deformations. We considered sets of points on two fixed surfaces and tried to build connections in the form of a line. We located a graph variable in the system which would affect the changes in the number of connections from more to less. The algorithm has been coded keeping in mind two weather conditions/ seasons - summer and winter. Considering the interrelated effect of the smart components on the façade and the unified effect of each of the four façades (2 leaves on each side, total 8 surfaces) on each other, the first step towards the framework of basic algorithm was to enable the active zone where the specific user or user group is located. With refer-

ence to this active zone, all the other smart components out of this region shall remain unchanged to environmental condition to save energy and complexity in maintenance while in operation. This centres the environmental problem to the effective region of the user's location and comfort zone.

SEASON – ACTIVE ZONE (given by user) –TIME ZONE (sun)—MODEL

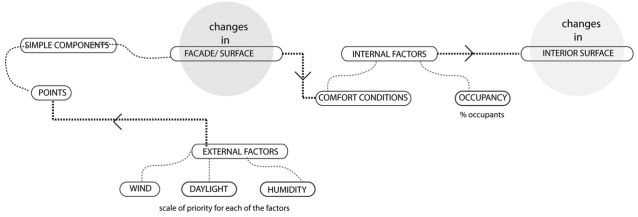

Figure 3. Explains the basic pseudo code formulated for the various internal and external factors interaction with the building skin in our computational system.

1.3. PROJECT SITE AND SCOPE

The project is conceptualised as a designed product, which would act as an envelope for an architectural space or a room or habitable space in any site across the globe. The original intent is to understand and explore the negotiation of the building skin and the environment with due calibrations in its responsive parameters to optimise the energy expense and indoor comfort conditions. Therefore, the decision that we have taken in the subsequent sections is considering its architectural application as a building envelope or façade anywhere around the world. For this research project, we assumed the site is located in a hot and humid tropical climate and thus the necessary calibrations on the surface parameters are done accordingly.

2. Design methodology

2.1. SURFACE CONSTRUCTION

A rectangular grid base (before embedding the smart components, which reacts to the environment) formulates the basic construction of the surface. Two kinds of surface typologies have been tested, one is triangulated and the other quad or square shaped. Due to dynamic surface changes, deformation possibilities and easy feasibility of fabrication, square shaped surface components are selected.

2.2. COMPONENTS OF SUN POINT

The entire 3D model setup of the enclosed space of four surfaces is tested against an actual sun component coded in Bentleys GC framework. The sun

essentially is the key external parameter that initiates and controls changes in the environment. Thus, the surface and eventually the three-dimensional space responds to the sun parameter. The arguments and variables created are, date, time (in hours), month and latitude (Reda and Andreas 2008). The next crucial step in the system was to connect the sun system with the surface grid points over the centroid of the embedded smart components. This enhanced the possibility of creating change in each component with any measurable change in the sun position (refer Figure 5).

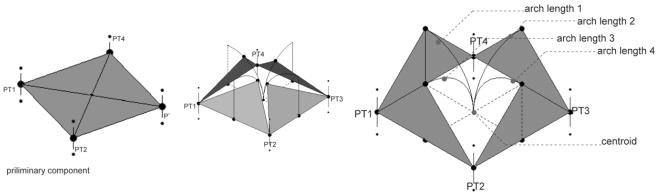

Figure 4. Depicts the smart component, populated over the surface at different opening levels.

2.3. SMART COMPONENT DESIGN

The component populated on the square shaped point grid on each façade is a simple square lamina further subdivided into four triangular sub panels, which could rotate on the edge of the square lamina. Each of the sub panel's tip or one of the vertices when closed meets at the centroid of the original base square surface. This form of design essentially eased the possibility of closed and open conditions of the panel, which worked as automated window panels. The opening and closing of the sub panels of the smart component was regulated by actuators, which triggered necessary response to the sub panels after observing substantial external or internal environmental change (refer Figure 4).

2.4. ADVANCED ALGORITHM

The angle between the centroid of the smart components to the sun was calculated, which necessarily is an important parameter to calculate solar insolation, radiation and day lighting.

2.4.1. Local and global change

Necessary changes were implemented on the opening amount of each of the sub panels of the smart components, based on the angular values obtained for the smart components inside the active comfort zone of the user's location, the active season and exact time. They could achieve five discrete states from 0 to 5. Here 0 signifies fully closed state and 5 being completely opened state.

This change is termed as local change as it affected the smart components. Another level of change demonstrated the change in the point grid over the surface, by making larger deformation on the topography of the surface. This change transformed the surface from a two-dimensional lamina into deformed undulated surface condition, which would be termed as global change. Both of the global and local changes are supervised by algorithmic control to instantiate a better surface geometry, which is optimised to sun position in a specific time at a specific season of the year (refer Figure 7). The inner surface is connected with the outer surface, with the help of thin stainless steel structural tubular connections (lines), which conveyed changes on the topography of outer skin into the inner skin, respectively based on season. This change is calibrated by a Cellular Automata rule (Wolfram 1994, Wissner-Gross 2008).The growth of these line segments or tubular connections was dependent upon the neighbouring line segment's state at any specific instant. Cellular Automata rule was chosen for its complexity and dynamic rule conditions to add variety in our system. The complex computation allowed surface response on both of the leaves of the façade due to relevant change in the external sun (refer Figure 5).

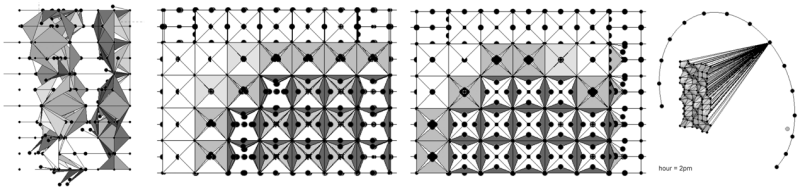

Figure 5. Shows the sun movement and the façade change accordingly at different times.

2.5. SUMMER AND WINTER CHANGES

Summer: Outer skin: Partially closed for sun and harsh climate protection
Inner Skin: Open to add in ventilation and active hot air movement to the outside.

Winter: Outer skin: Mostly opens for visually connected day lit spaces.
Inner skin: Closed to add day lighting, but to prohibit the entry of winter cold air.

2.6. WIND PARAMETER CONTROL

Basic philosophy followed while controlling the wind movement through the façade into the internal space is that wind flows from a positive to negative pressure gradient. Adding to that if the width of the inlet is narrower than the outlet then the wind velocity increases. Thus in the GC model, wind has been

exemplified as a curve with the starting point outside the room and the end point inside the room. The algorithm has been coded to facilitate lower cross sectional opening on the outer leaf of the façade towards the wind inlet zone and much wider cross sectional opening on the inner leaf of the same façade. This technique enhanced the wind inflow velocity during summer days thus alleviating comfort conditions inside the room. While the wind escapes from the room, the same strategy has been followed with narrower opening on the inner leaf while wider opening on the outer leaf (refer Figure 6).

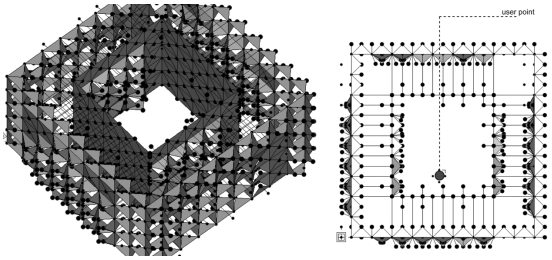

Figure 6. Depicts the construction of double-layered surface interconnected by cellular automata rules. The red point is the possible location of the user inside the space.

2.7. USER COMFORT AND TARGET PERFORMANCE

The user comfort in this research is limited to the parameters of day lighting, thermal comfort and natural ventilation criteria. The sun parameter acts as the initiator of the changes on the surface/façade that affects the global as well as the local change in the components of the designed system. The façade is differentiated into various sections depending on their location with respect to the user. The resultant form of the façade is dependent on the sun position as well as the user location at a certain time. This exemplifies the complex feedback loop between the user and the external environmental parameter where the façade plays an active role. The notion of such complexity is to reach the optimum user comfort level where system change is actively governed by external environmental parameters and user location. The system identifies active and passive zone on the façade system depending on user location. An active zone is marked by its proximity to the user. This selective mechanism entails energy saving while catering for user comfort.

3. Conclusion

With this ambitious computational research work, it has been tested and studied that responsive architectural primitives can be framed with an ecological perspective, wherein the architectural abode would not only provide spatial dimensions for habitation, but also shall respond and change in topology with the constantly changing environmental parameters. Parametric design formulates

this essential design condition, which enhances responsive design possibilities in simple living conditions. Clearly, such kind of architectural output has some inherent advantages and disadvantages which can be enumerated as:

Advantages of the proposed system could be: (1) Enhanced Indoor Air Quality and Ventilation, (2) Optimised day lighting, (3) User controlled building behaviour, (4) Unique architectural style of the envelope, (5) Optimised solar gains and insolation on building envelope, (6) Reduction in energy consumption, (7) Mass customisation.

Disadvantages of the proposed system could be: (1) Complex electromechanical system, (2) Might be expensive if not produced at mass scale, (3) High maintenance cost, (4) Highly educated labour needed for fabrication, (5) Weathering and noise production, (6) Life cycle cost can vary depending on scale.

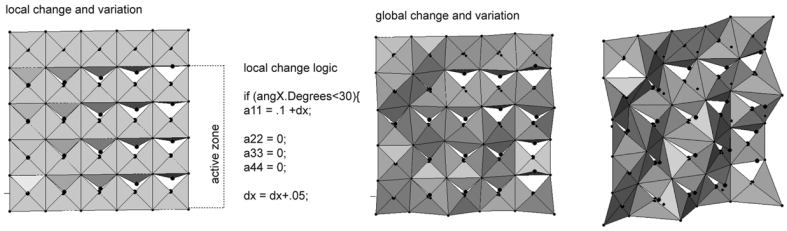

Figure 7. Shows the existence of local and global change i n the system respectively in summer and winter season.

3.1. SCOPE OF RESEARCH

The research focuses on the application of systems biology (a relatively new and major emerging field that focuses on the systematic study of complex interactions in biological systems, thereby using a new perspective to study them) to correlate the loosely coupled modularity in the architectural design that could otherwise be the cardinal feature of complexities. In this case, the systems biology of mammary epithelial cells and behaviour in different ECM condition was studied. The relational complexity in the cell behaviour with the various changes in the ECM manifests strong resemblance with architectural design components and their association with the contiguous environmental condition. The non-linear systems and relationships are mapped with the help of algorithmic tools to generate architectural manifestation and sophisticated feedback system, sustainability measures and performance related criteria's in a building system. The scope of the research lies in the exploration of the translation process from biological system into a refined architectural apparatus rather than performance analysis of a designed system with various tools to testify its relevance.

3.2. ACTUATOR BASED SYSTEMS

Actuator based systems have been put to applications in the façade of L'Institut du Monde Arabe, Paris by architect Jean Nouvel carrying several actuator based motorised apertures to control the light entering the building according to the weather conditions and season of the year. They are fully automated, not allowing the user interaction in the building to have a high granularity of control over their own space (Coelho 2008). Ageis Hypo Surface being another such innovative intervention in this field of responsive systems by Mark Goulthorpe exemplifying an actuator-based system manifesting dynamic reciprocity between surface components and external electronic stimuli from the environment. Unlike the actuator based interactive surface this research is focused on generation of an integrated system of building façade relying on reciprocation between environmental stimuli as well as individual user control in mutually exclusive form. The refinement of technology in actuator-based systems can mitigate any existing discrepancy. The generic idea of the actuator based autonomous system is perceived to contain a *Perception Layer*, a *Decision Layer*, and an *Action Layer* (Berger 2010). This basic framework of actuators would be synchronised to act in a feedback loop of both environmental control and individual user control. However, the actual set up of the framework of this actuator-based system is beyond the scope of this research.

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MATERIALISING THE PIXEL

A productive synergy

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Abstract. The composite photoreceptive field of the human eye receives photons emitted from a source and converts this energy into image information within the brain. The internal mechanisms of the contemporary camera imaging technologies represent yet another in a long history of attempts to technically replicate this procedure. The critical difference between the capacity of the human eye to receive quanta events or photons and that of a camera transmitting to a digital display device, rests in how much of the original signal can be recovered. This paper aims to show how the 'information deficit' associated with this technological conversion can be enhanced by the deliberate exploitation and re-arrangement of the camera's image sensor mechanism. The paper will discuss how the mapping of pixel grid geometries and colour filter array patterns at the vastly increased scale of building façades, imparts a materiality to urban form that modifies the visibility and performance of the corresponding virtual screen image. The exploration of the material adaptation of pixel geometries leads to a new technique that extends the working gamut of pixel-based RGB colour space and both establishes an index to develop material performance criteria and modifies the limitations of traditional viewing technologies.

Keywords. Pixels; sensor; CCTV; imaging; array; façades.

1. Introduction

As with past scopic regimes, the workings of contemporary digital imaging technologies use analogies that reflect current scientific theories concerning the functioning of the human eye. This technological analogy represents the photoreceptive field of the human eye as a pixel grid, but as Deering (2005) and

Hérault (2010) reveal, digital displays have a diminished capacity to receive quanta events or photons when compared to the human eye. This is based on the fact that a single pixel covers an angular region of only twenty-five cones in the fovea, meaning the pixel carries significantly less visual information than its human counterpart.

The persistence of the 'eye' analogy is made doubly problematic by the way digital imaging technologies determine pixel colour. There are, at present, two standard image sensor types, the complementary metal oxide semiconductor (CMOS) and the charge coupled device (CCD). The digital derivation of colour requires the placement of a gridded array of colour filters over these image sensors. These colour filter arrays, or CFAs[1], which can also take into account variations in hardware specifications and manufacturing quality, effectively screen colour and light from an emitting source. The averaging and approximation associated with the digital conversion of this 'source data' always involves a loss of visual 'data'. This situation is hardly remedied when techniques of interpolation between sensor readings are used to address this 'visual data deficiency' because the algorithmic extrapolation of colour and luminosity used in this process remains only an estimate. The inability to capture, recover or re-present the original visual 'data' means that these technologies produce outcomes that are both functionally and qualitatively very different from the human eye. In this context, the continuing desire to replicate 'what the eye sees' encourages only a conceptual limiting that minimises and 'normalises' the visual information field of the technology. Under these circumstances innate technological effects are treated as aberrations, resulting in the erasure of numerous visual effects in the image-making process. For this reason a technological re-thinking of the digital image itself is required: one that, by refuting the analogy of the eye, affords a more nuanced attitude to the technology, acknowledging the innate potential afforded by the mechanical transmission and mediation of the digital image.

Previous work by Matthews and Perin (2011) offers one way in which embracing the innate potential of these digital image technologies represents both new 'materials' and techniques for the designer. This research, as a response to the way in which city authorities have co-opted ubiquitous, Internet Protocol camera systems as a vehicle to promote the city, shows how the reception and transmission of imagistic content through these CCTV networks can be used to critically inform the design of new urban form. This work, involving the application of the CFA patterns at the scale of built form, exploits the 'visual data deficit' of the CFA pattern to produce aberrant effects that strategically altering the visual hierarchy of the webcam image. This

1 Colour filter array patterns: this abbreviation will be used henceforth in this paper.

modification of the viewing experience by exploiting the formal and chromatic qualities of sensor technologies can be taken further. Therefore, this paper will show, first, how a scalar matching of façade elements to alternative array patterns extends Matthews and Perin's previous work on façade visibility and colour and, second, how an understanding of f-stop intervals of the camera's zoom function can be used to tabulate a range of predictable visual effects. In this way the paper will establish an explicit material relationship between webcam technologies and built urban form that offers a reciprocal and synergistic imaging platform for designers.

2. Investigating image information technology

2.1. EXPLOITING CONTEMPORARY IMAGING MECHANISMS

Lucac and Plataniotis (2005) demonstrate that the operation of the internal camera mechanism establishes a direct relationship between the specific CFA pattern and the image quality received by a digital display device. Other research reveals that a direct scalar relationship between a camera's CFA and façade can be extended to different built scales and locations[2] (Matthews and Perin 2011). Together this work suggests, that if the strategic application of CFA patterns can productively enhance or diminish webcam visibility, then it should also possible to identify a hierarchy of array patterns that can be indexed, tabulated and redeployed to address a range of building design decisions. The principal investigations of this paper, therefore, explore how the traditional translation of data types by imaging mechanisms (in particular, brightness/luminosity and particle data) are directly affected by the use of non-traditional CFA's as building façades. The results of this investigation will then contribute to a broader understanding of how their discretionary application is able to privilege a range of different viewing experiences of urban space that is of consequence both virtually, through the screen, and physically, in actual built form.

2.2. PATTERN ADAPTATION HIERARCHIES

The operational principal of a CFA positions the pixel as the central determinant in the translation of image data. Technically, the camera lens focuses the light from a single point within the camera frame onto a specific arrangement of colour filters placed over the pixel array of an image sensor, to generate a charge proportional to that light.

2 For instance, the CFA pattern, when extrapolated and incorporated at increased scale into the physical pattern of building façades, can either enhance or reduce building visibility over the Internet due to its interference with the camera's operating mechanism.

In this context, the pixel is a single scalar element of a multi-component representation. This establishes a direct relationship between patterning/quality of the received image and the patterning within the CFA. Accordingly, when the charges created by the CFA mirror the pattern of elements within the transmitted image, any scaling of a façade pattern to the pixel resolution will affect its virtual counterpart.

This means the pixel is crucial to both the quality and quantity of data transmitted to any digital display device. Compared to the human optical capacity, which processes twenty five times more information than the pixel, (Deering 2005) the performance of the smallest complete image unit (only subdivisible into, green and blue subpixel components) operates at a far lower resolution. One solution to this is to rearrange traditional CFA patterns into new groupings that simultaneously maximise the translation of image data (He and Li 2007) and minimise the occurrence of problematic effects such as moiré patterns (Klompenhouwer and de Haan 2003).

John Savard outlines numerous pattern arrangement opportunities that could potentially exceed traditional CFA pixel layouts (Savard 2009). Savard's comprehensive detailing of unprecedented combinations, involving breakdowns into secondary RGB colours, underlines how rich an area of investigation this is. Despite the fact that CFA choice, 'critically influences the accuracy of the single-sensor imaging pipeline' (Lucac and Plataniotis 2005, p. 1260), it is surprising this area of research remains somewhat neglected. Surprisingly of the patterns investigated in this paper, only one, the traditional Bayer pattern, has been the subject of any investigation. To quote Lucac and Plataniotis (2005), '…there is no known work addressing the performance issues for other CFA's…in such a comprehensive and systematic way.' (p. 1260) Their investigation of ten different RGB CFA types ultimately proposes that while there is no 'perfect' CFA, that the CFA selection does indeed influence performance of the sensor pipeline, while simultaneously reducing image aberrations.

Clearly, the introduction of more adventurous and non-traditional CFA patterns into façade patterns would divest the pixel of its central role in image production. It would also deliver diversity to city image making by placing these technologies and their content into the hands of the designer. With this in mind, a set of tests was devised as a preliminary 'proof of concept' investigation into the effects façades using non-standard CFA patterns might have on the translation of image data. These patterns, selected because Lucac and Plataniotis (2005) identified them as the most effective (p. 1260), would only extend the list of known effects created when these virtual patterns are used in physical urban space. These results, that exceed traditional capacities of CFA

legibility, could then be used to identify, tabulate and organise these effects according to hierarchies using image-based performance criteria. The following details the outcomes of these tests.

3. CFA pattern adaptation tests

3.1. HARDWARE SPECIFICATIONS AND PARITIES

As in the previously cited research (2010), the tests were once again conducted using a Sony SX43E Handycam Digital Video Recorder. The operation of this technology is identical to that of the Sony SNC-RZ50N network camera with the exception of specific operational capacities that were again taken into account when calculating results.

3.2. TEST CONSTRAINTS

- Zoom factor - the test results of interest are between 1x and 26x, which is the area of operational parity between the two camera mechanisms.
- Light source/aperture plane distance is at a relative scale of 1:10. i.e. the 5 metre light source/aperture plane distance in the test correlates with a 50 metre distance in an exterior environment. Likewise, the CFA patterns used are 150 mm^2 to correlate with a typical building façade element of 1.5 m^2.
- The lighting source is a single 30W Par 64 RGB LED (with an output equivalent to the traditional 300W Par 56).
- The tests are conducted in low ambient light conditions to simulate the type of urban night condition that would be available over the Internet camera.

3.3. TEST STRATEGY AND PROCEDURE

Tests were conducted using two types of RGB CFA patterns: those investigated by Lucac et al., based upon their ubiquitous deployment within the single-sensor imaging pipeline; and two other modified RGB patterns, one based on the traditional Bayer array pattern, and the other devised to remove the dominant ‘R’ component of the pattern. The latter pattern also comprises two single vertical strips to test against the concept of the efficacy of ‘pseudo-random’ patterns (Fillfactory 2010).

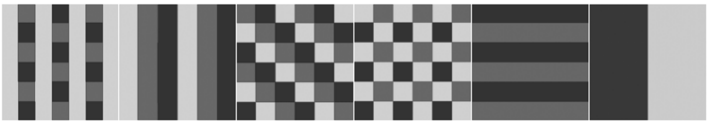

Figure 1. RGB CFA patterns (from left to right) N1: Yamanaka CFA; N2: vertical stripe CFA; N3: diagonal stripe CFA; T1: Bayer CFA; T2: partial horizontal stripe CFA; T3: partial vertical stripe CFA.

The patterns were applied as a transparent colour film to a 3 mm acrylic base and placed in front of a single LED lamp to simulate the type of interior lighting conditions that would operate at night within an urban context. The camera was then placed at a distance of five meters from the light source. Acting as a scaled approximation of the standard Internet camera viewing distance from the image source, this enables specific or aberrant features of the recorded image to be correlated and tabulated in accordance with the performance of the camera's zoom or f-stop increments. It was determined that the assessment criteria to be applied to the performance quality of these patterns should focus on their ability to produce higher legibility in façade applications. These criteria were luminance emission levels, cited as the highest acuity for the human eye (Fillfactory 2010) and data or particle transmission levels, to observe the comparative quantum of digital information. The test results were processed using the luminance visualisation and measurement function of *ImageJ*[3]and, subsequently, a combination of a binary converter and particle assessment function. Procedurally, video footage of stills falling within the appropriate f-stop range were imported as a 'stack' of discrete image units and then processed to determine both luminance and particle criteria. In the latter case, the images were converted using the Floyd Steinberg Dithering algorithm, which converts images into binary form so that they can be counted and measured.

3.4. TEST 1 – LUMINANCE TESTS

3.4.1. Results

The individual patterns were labelled N1; N2; N3; T1; T2; and T3 (Figure 1).

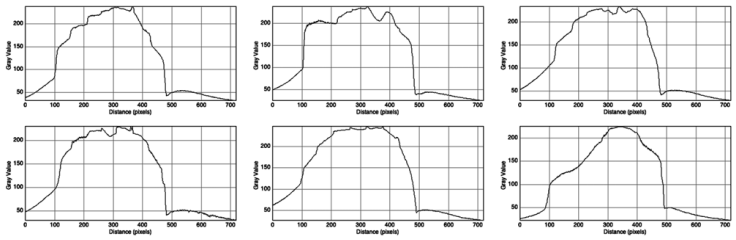

Figure 2. Comparative luminance emission levels of patterns N1-N3 (top row) and T1-T3 (bottom row) between F1.8 and F3.8.

- The luminance levels of pattern T2 (the incomplete horizontal Bayer pattern) exceeded the luminance levels of all other patterns (Figure 2).
- The luminance levels of patterns N2 and N3 were the highest of the CFA patterns currently in use, followed by that of patterns T1 and N1 (although the

3 *ImageJ* is open-source JavaScript medical imaging software.

lower result for both N1 and T1 might potentially have been influenced by the inclusion of more green due to the repetition of the pattern within the selected viewing frame (Figure 2).
- The luminance level of pattern T3 was the lowest (Figure 2).
- The maxima (brightest spot) count was the highest for patterns N1 and N2 followed by T3 (with the lowest luminosity level) and then T1 and T3 (Figure 3).
- The maxima (brightest spot) count was the lowest for pattern T2 (which had the highest luminosity level, Figure 3).

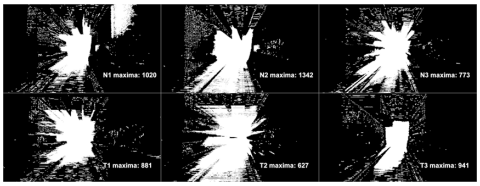

Figure 3. Comparative maxima spot counts of patterns N1-N3 (top row) and T1-T3 (bottom row) between F1.8 and F3.8.

- Chroma visibility in all patterns operated as follows: on the inward zoom, red was the first colour to become completely visible at f2.6, followed by blue at f3.0 and finally green at f3.2. On the outward zoom, the same order of visibility was apparent, however, the visibility period was extended with green remaining completely visible until f2.8, blue until f2.4, and red until f2.

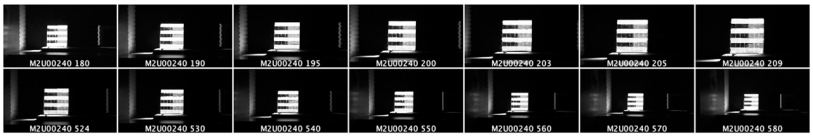

Figure 4. Chroma visibility progression for according to camera f-stop intervals for CFA pattern T2.

3.4.2. Observations

- Pattern colour distribution and combination influences visibility: red is the most visible followed by blue while green is the least visible. Any colour combination that includes red advances visibility, particularly if it is just one other colour (although a combination of red and green was not tested here). The combination of blue and green is the least visible.
- Pattern orientation influences visibility: vertical stripes are the most visible, followed by the diagonal and then vertical except when red is present.
- Patterns with more evenly distributed luminance information have higher visibility (Figure 5).
- Maxima (brightest point) occurrence is higher in the vertical stripe pattern.
- There is a difference in the progression of colour visibility between the inward and the outward camera zoom journey.

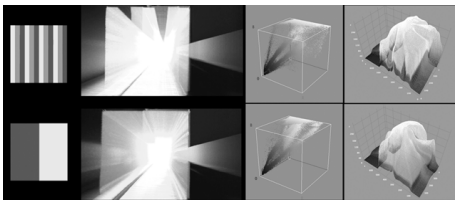

Figure 5. ImageJ visualizations of luminance distribution for N2 (top) and T3 (bottom).

3.5. TEST 2 – PARTICLE DATA TESTS

3.5.1. Results

- The data count for patterns N1 and N2 was the highest (based on the vertical stripe), followed by T1 and T2 (checkerboard and horizontal stripe).
- N3 transmitted significantly less data than the above.
- T3 transmitted the least data (undifferentiated double vertical stripe)

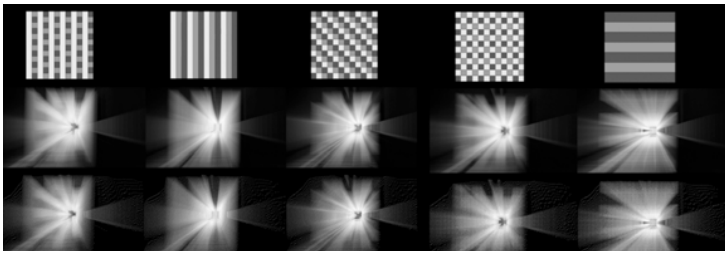

Figure 6. ImageJ montage of (top row) CFA patterns; (second row) standard deviation (variation in pixel distribution) for CFA image stack ;(third row) translation of standard deviation into binary information using Floyd Steinberg Dithering algorithm; and (bottom row) ImageJ particle data count for all patterns.

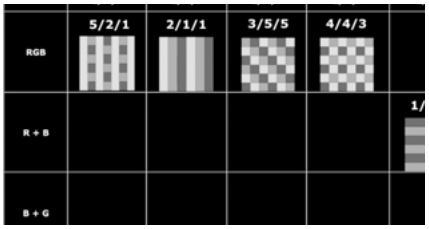

Figure 7. Index of material performance according to colour combination and pattern showing relative luminosity (L), maxima/brightness (M), and particle data (P) values.

3.5.2. *Observations*

- These results correlate with the luminosity and maxima (brightest spot) readings indicating that image legibility is affected by pattern orientation, distribution and colour combination.

4. Conclusion

While these results represent a preliminary investigation into the adaptation of CFA patterns as formal constituents of building façades, it is evident that this can be strategy used to manipulate building visibility within a virtual context. Although the thorough investigation of all permutations of RGB CFA's remains incomplete, these results indicate a direct relationship between façade pattern and the internal permutations of these patterns: specifically distribution, orientation and colour combination. Moreover, these results can be indexed to formulate an operative palette and hierarchy of formal visibility that the designer can reference and incorporate into building façades.

Clearly this work shows that the manipulation and scaling of façade materiality to pixel arrangements, when transposed at different scales, results in unprecedented visual effects. In establishing a functional link between digital viewing technologies and the material urban environment, one opens a synergistic imaging platform where the technologies of the pixel are no longer a proprietorial concern but can be adapted to actively engage the Internet viewer. While these results remain conditional, the matching of façade to CFA patterns clearly has formal and material consequence that impact on urban images. Furthermore, the linking of pattern to light and colour means that one can indirectly inform interior spatial, and hence programmatic, organisation. Importantly, this strategic and tactical use of image technology can only occur by dispensing with the dual notions that the camera is an eye and that these technological effects are 'aberrant'.

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LOCAL OPTIONEERING

Producing complex geometries through opportunistic networking

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Abstract. How can small architectural practices participate in contemporary architectural experimentation? One route is through engagement with complex, parametrically controlled geometries. However, the utilisation of such geometries by small practices is comparatively rare. We sought to explore the circumstances of such engagements with the hope of finding what can make them more feasible. To this end, we developed a purpose-specific methodology based on the simulation of an integrated design workflow. To develop and assess this simulation, we exposed a hypothetical project to multiple stakeholders including fabricators, engineers, architects, builders, clients, planning authorities and researchers. The outcomes suggest that the conceptual stance described as optioneering in application to large projects can also be productive at smaller scales.

Keywords. Digital architectural design; digital fabrication; local expertise; parametric geometry; design innovation; optioneering.

1. Introduction: elitist complexity

Experimentation with complex, curvilinear geometries is prominent in the contemporary architectural thinking. Their development, utilisation and questionable desirability belong to a broad theme that is well beyond the confines of this paper. Instead, we consider what frames the implementation of such geometries when the aspiration to use them is already present.

An increasingly common method of producing complex forms is through parametric geometry. Parametric design techniques are said to offer flexibility, speed of exploration, means to process large amounts of data and the ability to fabricate directly from computational models.

Recently, a number of high-profile and geometrically complex projects were completed in Melbourne. These include Federation Square by Lab Architecture Studio, Rectangular Stadium by Cox Architects and Southern Cross Station by Grimshaw Architects. More are on the way, e.g., cf. The Swanston Academic Building by Lyons Architects, due for completion in 2013. Exploration of complex geometries in these projects indicates sustained local interest in their possible applications. This local interest, combined with other regional characteristics (cf. economic and cultural contexts, population size and density, available institutions, etc.), frames and limits our findings.

Kieran and Timberlake (2004, p. 11) argue that fabrication (and not construction) can overcome the linear dependence of quality and scope on cost and time, allowing the art to transcend resources. They also suggest that as a result of the slow uptake of fabrication within the construction industry, current practices have become outdated, inefficient and technically limited (Kieran and Timberlake 2004, Woudhuysen and Abley 2004). We observe that this lack to technical aptitude – especially at the local level – has led to a widespread assumption that the production of complex geometries is unattainable by all but the well-financed international elite, working on very large projects. Unfortunately, small practices frequently fail to test this assumption and accept that complex geometries are beyond them.

To illustrate, the aforementioned projects were produced by medium (11 to 30 employees) or large (more than 30 employees) firms (these size definitions were informally advised by the Australian Institute of Architects). While exceptions exist (in Melbourne, cf. McBride Charles Ryan, Harrison White Architects and HATZ Architects), our survey of the local field indicated that small (less than 11 employees) practices are rarely involved in geometrically advanced, computationally sustained projects. The initial interest in the research presented in this paper was provoked by this observation. Our literature survey demonstrated that – currently – there is little written material on factors influencing the production of complex geometries by small practices. Consequently, there is little guidance on how to cope with limitations. These limitations extend well beyond purely technical. We are aware that architectural experimentation is typically produced for powerful or affluent clients and that local builders typically have little interest in or means for innovation. While the overarching motivation of our work is to contribute to the change in this culture, the general discussion of these themes is beyond the scope of this paper. Instead, we hope that this report on our research-in-practice can serve to indicate the directions for further study and provoke useful discussion.

2. Research method: simulated design development

To explore our research field, we organised a hypothetical project (called *Ripple*), which proposed a complex facade of articulated ribbons. We chose the ribbon as a geometric system because it provided a rich test case. With no local project with a similar approach, a custom production process had to be investigated and designed. This process considered finances, procurement patters, available expertise, design technologies, construction methods, material choice, structural systems, stakeholder jurisdiction and so on. To reveal the relevant factors, we organised a series of consultations with a broad range of stakeholders including fabricators, engineers, architects, builders, clients, planning authorities and researchers. During the initial search (that simulated an approach available to a typical small practice), we contacted potential contributors because we knew of their past involvement in relevant projects or estimated that their expertise could be repurposed to the project's goals. Their names were sourced through publicly available project credits or through personal recommendations by local peers. In accordance with the typical small-firm work practices, all contributors were local. By confining the project to the local setting we gained direct access to the stakeholders and could utilise our knowledge of the local context. On the other hand, the decision not to extend the search internationally constrained the palette of expertise and technologies. In the future, it would be interesting to show how small local practices can engage with international experts, for example through online communities.

To develop an informed, inclusive understanding of the factors at play, our consultations with local experts were integrated into the iterative development of the project. During these consultations, contributors were asked to comment on specific aspects of the design, drawing from their areas of expertise. The hypothetical, non-commercial nature of the project meant that its development differed from those of real projects in a number of aspects. For example, issues such as internal program, floor areas and servicing were not considered in great detail during these meetings. The project did not go through a realistic procurement process and so on. However, the project's theme was verified with local architects who confirmed it as parallel to their past work. In consultations, all experts were asked to consider the project as a real practical challenge. Consequently, the conversations replicated those possible (or typical) during normal research and development. The consultants frequently used real (past, ongoing or future) projects to source examples or evidence. The ensuing discussions could highlight relevant issues, test assumptions and generate new ideas. After each consultation (or a series of meetings), the design was rearranged according to the stakeholder's advice and then revealed to the next expert. Figure 1 shows six key stages in this development process.

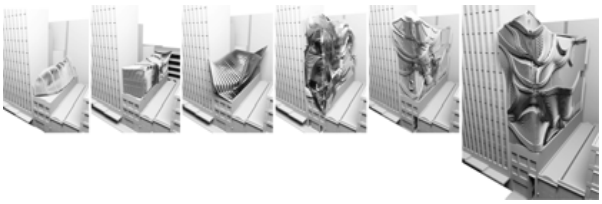

Figure 1. Key stages in the development of the Ripple project.

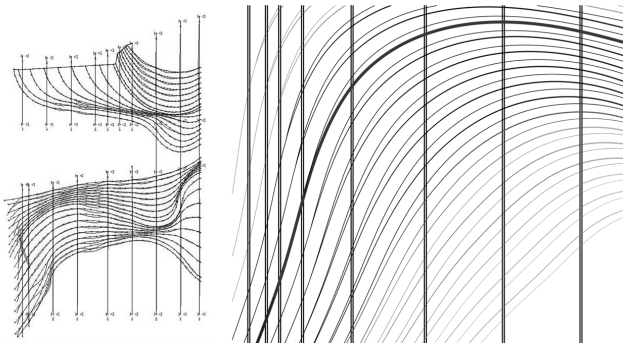

Figure 2. Left: evaluation of deflection and generation of vertical distributions in Space Gass. Right: bunching of vertical support members. The horizontal offset between vertical support members can be varied so as to keep ribbon-segment lengths similar.

An example of the interaction that informed this development can be seen through communications with Jon Anderson, a structural engineer with a special interest in parametric design. The consultation with this expert focused on resolving the vertical elements supporting the ribbons. Anderson's Grasshopper to Space Gass plug-in (Figure 2, left) allowed a variety of steel profiles to be applied to the vertical members in order to establish the minimum thicknesses necessary to satisfy vertical and horizontal deflection. It also revealed that the vertical structure could be optimised by bunching the support members in relationship to the angle of the ribbons (Figure 3, right). This association could then be automated in the parametric model before the project was shown to the next stakeholder.

Key stakeholders saw the project multiple times and were able to see how their suggestions and the input of others affected the development. It was particularly beneficial to conduct these consultations in the work places of contributors – flexible access to the tools and technologies available there frequently led to spontaneous ideas and supported innovation. For example, such benefits were obvious when working with Rock Martin, specialist metal fabricators. In the discussion on how to fabricate an undulating metal ribbon economically,

they were able to demonstrate how a jig built for a previous project could be modified to produce an incremental curve over a laser-cut metal profile. The tangible understanding of the mechanical process gained through this encounter expanded the design space and led to new design decisions.

To conclude, the adopted methodology proved effective as a research tool. Multiple experts became involved in the project, to which they contributed with enthusiasm and without remuneration. On the basis of this experience, our impression is that a similar process could be adapted to serve as a research phase in a real project. We intend to test this speculation in subsequent work.

3. Limiting factors

The feedback gathered through our consultations was specific to the project. However, some of our observations can be applied to generic situations operating under similar constraints, not as normative recommendations but as suggestions for exploration. We realise that deeper and/or broader research would reveal a broader range of limiting factors, beyond those directly encountered in our project. These factors might include socio-economic limitations, cultural and aesthetic concerns, the risks of narrow specialisation for small practices, the reasons behind firm sizes, legal regulations controlling professional responsibility and the need to justify experimentation in a competitive market place.

The limited range of factors emanating from our research is presented in three categories. While these categories have emerged from the consultations, they are a narrative convenience rather than an ontology and should be understood as such.

3.1. EDUCATION

Educational factors relate to the slow rate of professional development in the construction industry. Adrian Stanic, director at Lyons Architect, a medium-sized firm engaged with the contemporary digital discourse and Jon Anderson (HIVE Engineering) both commented that a prevailing inability to keep up with conceptual and technical developments is detrimental to architectural, engineering and building professions. Stanic commented that even progressive architecture firms such as Lyons Architects tend to rely on the skills brought in by recent (read inexperienced) graduates as a means of staying in touch with developments in architectural computing. Smaller firms typically do not have the resources needed to explore new or experimental processes. Anderson commented that the only other engineering firm that he knew to have a thorough understanding of parametric software, in Melbourne, was Arup.

There are certain benefits that come with using older and more labor intensive CAD programs, state fabricators from Rock Martin. Such software (e.g., AutoCAD) requires more user input and can focus the designers' attention on how individual elements will be fabricated and joined. The laborious CAD drafting then acts as a virtual check list. However, manual drafting also limits the possible complexity. A possible response to this situation, given the limited resources, is partial and targeted implementation of parametric models for the key components of projects.

Ross Berryman, a builder with more than 20 years' experience, commented that builders and other consultants are often struggle to read 2D architectural drawings. Mistakes regularly occur due to misinterpretations, the risk of which is compounded as the project becomes more complex. Berryman advocated the use of 4D visualisation to convey assembly and construction processes and to detect potential problem/collisions, for instance spanner swing radiuses (small scale) or crane fixing points and panel tessellation/stacking (large scale). A parametric model can supply such representations rapidly and conveniently. For example, a similar process was used successfully by Drew Williamson, the project architect from McBride Charles Ryan. When a slight change occurred on site during the construction of their Klein Bottle House, Drew updated his 3D model and then supplied screenshots directly to the builder on which he annotated the corrected cut angles and member lengths.

To conclude, building and maintaining expertise is a major challenge for small architectural practices. How can digital-tool builders, educators or practice communities address this need? We are not ready to answer this question but suggest that this issue requires the attention of the research community. For example, it would be interesting to explore whether strategies that are now emerging in large scale projects can be applied at the local level. Can open-source knowledge-sharing contribute to the development of local expertise? What can reward such broader sharing in the context of patentable technologies and for-fee advice? Can small local practices import external expertise through optioneering and team building as it is implicated by "integrated project delivery" or "multidisciplinary design optimisation" approaches? As Carpo (2011, p. 162) observes, some large offices have recently started to offer comprehensive BIM packages for smaller architectural firms, including software, consulting, and possibly full project delivery. Such initiatives raise further questions on the balance between pre-packaged commercial tools and more flexible aspirations of computational creativity. Do small practices have to buy all of the necessary expertise? Can they extend their explorations by attracting students and recent graduates? How can universities and professional bodies support them in this process? In our research, the broad

and ongoing need for education well beyond the university's environments emerged as a unique contemporary challenge that requires further focused attention.

3.2. COMMUNICATION

Factors of communication refer to the transfer of expertise and information between stakeholders. They include difficulties in transferring geometric information between software packages, while maintaining parametric capabilities. Stanic (Lyons Architects) has found an inability to stage such a process often produces a situation where a particular stakeholder begins using parametric software but finds that the benefits are limited because they cannot efficiently communicate with other parties. For example if Lyons Architects were to build a detailed parametric model using Revit and then pass it on to a services engineer who was unable to add ducting to the model, the potential for detecting collisions becomes unavailable, undermining the usefulness of the model.

Within Melbourne, small practices have accumulated methods that begin to address this issue. For example, Jon Anderson (HIVE Engineering) developed plug-ins that allow automated transfer of large quantities of geometrically complex information from Grasshopper, Rhinoceros 3D and ArchiCAD (examples of design software) to Space Gass (engineering evaluation software). His system could support the rapid, accurate structural evaluation and optimisation of *Ripple's* ribbons and vertical members. Marcus White, a partner at Harrison White Architecture, has taken a different approach wherein he uses the capabilities of 3DS Max, in conjunction with a number of plug-ins, to test a variety of factors that would otherwise be in the domain of a specialist consultant. He keeps a project in 3DS Max for as long as possible, maintaining maximum flexibility, before moving the project into documentation software.

As was already mentioned in the discussion on methodology, the physical proximity of stakeholders can be advantageous because it allows collaborative sketching of ideas supported by tangible interactions with prototypes, materials and fabrication processes. For instance when working with Rock Martin, ideas for the potential fabrication of a triangular-profile ribbon were quickly sketched and developed (Figure 3) through face-to-face interaction where designers was able to direct fabricators' expertise to support their design intent. Their conversation resulted in a deeper shared understanding of project goals and technical limitations.

According to Stanic (Lyons Architects), another issue that arises when dealing with experimental projects is who takes responsibility for the complications that are likely to occur and who pays for them to be remedied? This

mentality is encouraged by the segregation of the building industry and the separation of legal responsibilities. Stanic proposes that collective practices or alliances, where members (architects builders and clients) enter into an agreement in which liability is equally shared, can offer a solution which could potentially allow for greater experimentation.

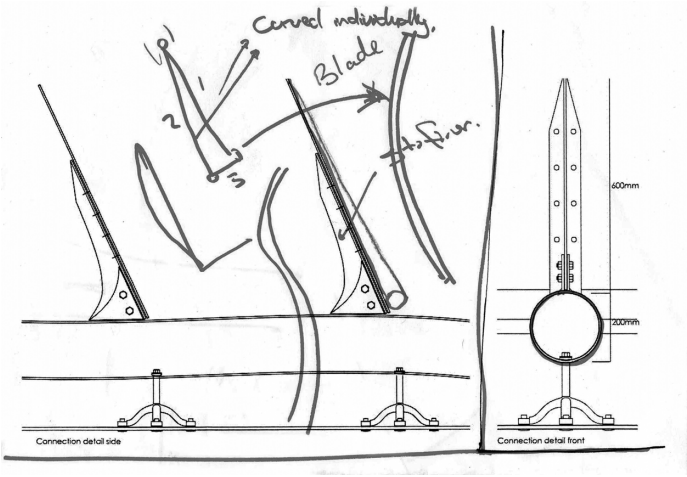

Figure 3. Sketching of ribbon options.

To conclude, our observations demonstrate that small practices tend to rely on face-to-face communication and local support networks. Consequently, it is reasonable to speculate that further integration of architectural computation into their workflows will need to cohere with these working practices. For example, both Marcus White (Harrison White Architecture) and fabricators at Melbourne Laser Cutting stressed the need to understand how information could be most conveniently transferred and presented to different stakeholders. As Di Maria and Micelli (2008, p. 275) observe, "literature on local manufacturing systems and industrial districts has given little attention to the ways cognitive processes are organised and take place within local contexts." Hence, future work could focus on flexible communication protocols that integrate physical and digital communication with the aim of supporting rapid evaluation of multiple options, again in parallel with the similar ambitions that are currently being explored at larger scales (e.g., cf. Holzer 2006, 2009).

3.4. PROCUREMENT

Stanic (Lyons Architects) and Anderson (HIVE Engineering) have both found that clients are often wary of the risks associated with an experimental

project and choose to pursue more standard approaches as a result. Furthermore, Anderson (HIVE Engineering) and Drew Williamson (McBride Charles Ryan) agreed that one of the primary factors limiting broader utilisation of complex geometries is the difficulty in assessing the additional costs. Anderson believes that when BIM will allow architects to state that, for instance, a ribboned façade will cost 15% more than a typical glass curtain wall, clients will be more likely to accept more complex proposals. Williamson (2011, p. 411–413) adds that through the use of digital 3D models, costs can be essentially parametricised but expresses concern for the "considerable limitations" to innovative design caused by the predefined-family paradigm used in most BIM applications. The restricting factor is not whether a particular system is buildable. Instead, it is in the relationship between extra cost and demonstrable additional benefits. In these cases the reasons – such as building performance or cultural considerations – must extend beyond the obvious geometric novelty.

Marcus White (Harrison White Architecture) comments that budgets that do not allow for research and development costs can lead to stagnation in architectural experimentation. In response to this Anderson (HIVE Engineering) suggest that small, specialist practices with highly focused interests are able to offer cutting edge expertise at lower prices than larger firms, as they do not have the high overheads that the larger firms carry. This statement promises an interesting alternative because it is unlikely that small practices will ever be capable of sustaining the broad expertise necessary for the production of all types of complex geometry (even without considering the much broader spectrum of other technological opportunities). However, this approach requires an adequately rich local industry able to supply such specialists as well as a developed local community able to connect such specialist into task-specific teams. An engagement with this field can then be – again – interpreted as optioneering; or an opportunistic methodology that takes advantage of the available expertise and allows these constraints to inform design directions.

4. Conclusion: towards local optioneering

This paper began with the conceptualisation of the "local" as an imposed characteristic that comes with limitations. These limitations are certainly real. However, our research demonstrated that local conditions also have pragmatic advantages and should not be automatically interpreted as constricting, merely as different. The exact nature (or rather – productive interpretations) of this difference has to be the focus of future research work. This line of thought can be further reinforced with the ideas emanating from the overarching discourse, for example on sustainability and creative communities where the role of glo-

bal-local manufacturing is being actively discussed. In particular, directions of future research, suggested by our work to date, might include a comparative study of a broader variety of local contexts and a broader survey of local capabilities extending beyond personal impressions of individual experts.

The aim of this paper was to show that – according to our limited observations – the very challenge of local production of complexity requires engagement in contemporary architectural discourse and experimentation. The consultations enabled and motivated by the *Ripple* project suggested that the difficulties for small practices to undertake geometrically complex projects are significant. If they are to be overcome, further work at multiple levels is necessary. Given the amount of architecture designed by small local firms, and their influence within the local communities, this work appears to be important.

As a preliminary suggestion, this paper proposes optioneering as a useful attitude towards local and small-scale architectural designing that utilises contemporary computation. This attitude appears productive because it suggests flexible and opportunistic methodologies that make the best use of available skills and technologies. In the case of Melbourne, we discovered available expertise, technology and – crucially – considerable enthusiasm towards computationally sustained explorations. This enthusiasm suggests that a way forward can be via the community driven effort towards a supportive ecosystem of stakeholders. Indeed, we are actively participating in such efforts. To date, they include a local case-study discussion group (Computational Design Group, Melbourne) and an institution-agnostic education initiative (ExLab, or Experimental Design lab) but the discussion of these will have to be reserved for future publications.

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6A GENERATIVE, PARAMETRIC, AND EVOLUTIONARY DESIGN III

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MULTI-CRITERIA EVOLUTIONARY OPTIMISATION OF BUILDING ENVELOPES DURING CONCEPTUAL STAGES OF DESIGN

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Abstract. This paper focuses on using evolutionary algorithms during conceptual stages of design process for multi-criteria optimisation of building envelopes. An experiment is carried out in optimising a panelled building envelope. The design scenario for the experiment is based on the scenario described in Shea et al. (2006) for the building envelope of the Media Centre Building in Paris. However, in their research, the optimisation process only allowed panel configuration to be optimised. In this paper, the task is to approach the optimisation of the envelope of the same building, assuming it to be in the early phases of the design process. The space of possible solutions is therefore assumed to be much wider, and as a result both external building form and internal layout of functional activities are allowed to vary. The performance intent of the experiment remains the same as that of Shea et al. (2006), which was to maximise daylight and minimise afternoon direct sun hours in the building at certain specific locations.

Keywords. Multi-criteria optimisation; building envelopes; conceptual stages of design evolutionary algorithms; parametric design.

1. Introduction

Building envelopes can be optimized for performance criteria that are often in conflict with each other and are also difficult, if not impossible, to optimize manually. Hence, there is an opportunity to explore the use of computational design and optimization tools that facilitate the design of optimized building envelopes for multiple criteria. Previous approaches to computational building envelope optimization include both evolutionary and numerical optimization approaches (Bouchlaghem 2000, Gagne and Anderson 2010). The problem

with most of these approaches is that they target the detail design stage when most of the design is already fixed, thereby losing on the opportunity for a more holistic exploration of design alternatives.

This research explores the use of evolutionary optimization techniques (Holland 1975, Goldberg 1989) to optimise a building envelope during the conceptual stages of the design process for multiple conflicting performance criteria. To deal with the evaluation of multi-objective optimization problems, Pareto ranking techniques are used (Goldberg 1989, Fonseca and Fleming 1993).

The design scenario for the experiment is based on the scenario described in Shea et al. (2006) for the building envelope of the Media Centre Building in Paris. The building consists of a 12 m × 20 m × 8 m parallelepiped shaped space, split into five internal spaces namely, gallery wall 1, gallery wall 2, meeting area, reception and office (RP1, RP2, RP3, RP4 and RP5 respectively) all with different lighting performance requirements as shown in Figure 1.

The building envelope to be optimised can be imagined as a pixel grid of panels that wrap the walls and roof of a building, where each panel can accommodate several types of panels with different lighting and cost properties (e.g. opaque, clear glass etc.).

In the design experiment by Shea et al. (2006), only the panel configuration was optimised. The external envelope geometry and the internal plan configuration were predefined and were not allowed to vary. However, during the conceptual stages of the design process, only optimising the panel configuration may not be sufficient. It may be possible to find better solutions by optimising other aspects of the design in tandem with the panel configuration. In this paper, the task is to approach the optimisation of the envelope of the same building, assuming it to be in the early phases of the design process. The space of possible solutions is therefore assumed to be much wider, and as a result both external building geometry and internal plan layout are allowed to vary.

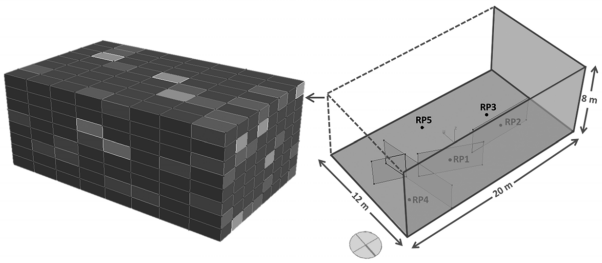


Figure 1. Paris media centre space and response point (RP1–RP5) specification.

The demonstration is divided into two experiments. In the first experiment the panel configuration and external geometry of the building are varied. In the second experiment, the panel configuration and the internal floor plan of the building are varied. The performance intent of both the experiments remains the same as that of Shea et al. (2006), which was to maximise daylight and minimise afternoon direct sun hours in the building at certain specific locations.

2. Design method

An Evolutionary system called Dexen is used to execute the optimization process. This system is coupled to Sidefx Houdini, an advanced procedural CAD application that is used for both design development and design evaluation procedures (Janssen et al. 2011). This application includes a visual data-flow modeling (VDM) interface that allows users to create complex parametrised procedures. With the evolutionary design method, the set of parameters are referred to as the genes (which together from the genotype), the model is referred to as the phenotype, and the results from the evaluations are referred to as a set of fitness scores. The evolutionary design method requires three key procedures to be defined; namely the development procedure that generates a phenotype from a set of genes, one or more evaluation procedures that calculates fitness scores by analyzing and simulation the phenotype, and a feedback procedure that performs genetic reproduction based on the fitness scores. The developmental and evaluation procedures are defined using Houdini using the VDM approach. The feedback procedure is generated automatically by Dexen based on various standardized settings. This procedure will rank groups of phenotypes using a standard Pareto ranking method, and will then create new genotypes using crossover and mutation operators.

3. Lighting analysis

For the evaluation procedures, the Radiance simulation program is used for calculating two different lighting performance criteria: lighting level and number of sun hours. Calculations are performed for certain predefined points in the model. For lighting levels, the Daylight Factor is calculated for each point. For sun hours, the total number of hours that a point receives direct irradiance from the sun of at least 120 W/sq-m is measured. (The World Meteorological Organization refers to this as ‘sunshine duration’.)

Within Houdini VDM nodes have been created for linking Houdini to Radiance. These nodes generate the required input files from the Houdini model and then execute the radiance program.

4. Experiment A

In the first experiment, parameters related to the panel configuration and external geometry are varied.

4.1. DEVELOPMENTAL PROCEDURE

The developmental procedure for Experiment-1 involves creating the parametric model in Houdini. Though the floor plan and the internal arrangement of spaces is maintained as in Shea et al. (2006), the parameters governing the shape of the parallelepiped (the envelope) are varied along with the panel types. The three planes are divided into a total of 192 panels, each of which can be assigned a different material. For the purpose of this experiment, the materials are assumed to be the same as those described in Shea et al. (2006) i.e. opaque panels, clear glass panels, diffusing glass panels and shaded glass panels, as indicated in Table 1. In this experiment, the parameters that define the phenotype are the 192 panels and the movement of points P1, P2, P3 and P4 in the X, Y and Z direction as shown in Figure 2. The movement of points in X and Y directions controls the slope of envelope in that direction and is given a range to move towards and away from the building by 3 m. The movement of points in Z direction controls the height of the internal spaces in the building and is given a range of 4 m to 8 m. As the shape and form of the envelope changes, the size and shape of the panel change accordingly, still maintaining the same number of panels throughout the evolutionary process.

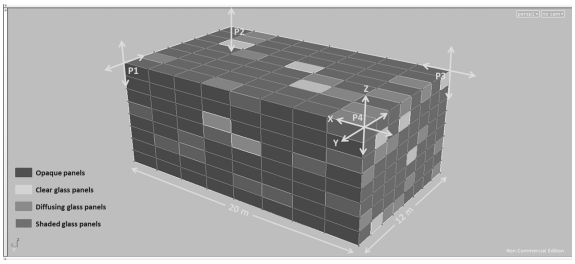


Figure 2. Points that define the geometry of the envelopes.

TABLE 1. Panel materials.

Panel material	Light transmission	Direct Sun?	U-value (W/m2k)	Cost (Euros)
00. opaque	0%	No	0.3	300
01. clear glass	75%	Yes	1.8	450
02. diffusing glass	60%	No	1.8	500
03. shaded glass	25%	No	1.6	600

4.2. EVALUATION PROCEDURE

There are in total five performance criteria for which the strength of the phenotypes will be assessed. The evaluation procedures are defined using Houdini.

The overall optimization strategy can be defined as follows:

- Maximize daylight factor at response points (maximum of 15%)
- Achieve desired sun hours at response points
- Minimize average U-value of the panels
- Minimize overall cost of the panels
- Achieve desired height at each of the five internal spaces

The first four criteria were part of the performance criteria defined by Shea et al. (2006). The last criterion of height has been added for the purpose of this experiment. Each internal space has different height requirements, taking into consideration factors such as air-conditioning, privacy, lighting etc.

4.3. ANALYSIS OF RESULTS

The 3-D chart in Figure 3 represents 10,000 solutions, with daylight factor, cost and U-value plotted along the X, Y and Z axis respectively. Sun hours are indicated with colour coding. (On this chart, the fifth performance criterion - space height, also represented through colour coding - is not shown.) A score of 5 indicates that the solution has satisfied all the rules set for that evaluation criterion of sun hours or height. As shown in Figure 3, the solutions with the maximum score of 5 for 'sun hours' gradually get denser towards the origin. The Pareto front of these 10,000 solutions can be derived by filtering points in the 3D graph.

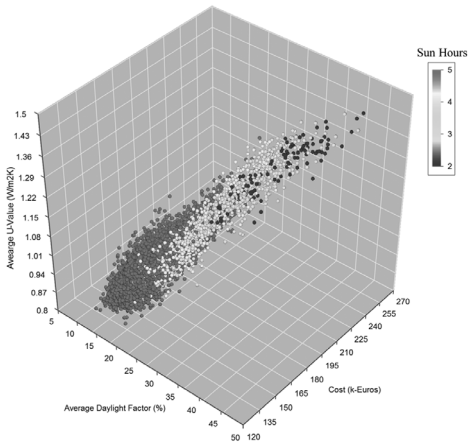


Figure 3. 3D graphs representing the 10,000 solutions for Experiment A.

The Pareto optimal solutions shown in Figure 4 represent the final outcome of this experiment. The score for 'sun hours' and 'height' criteria has reached the maximum for all the solutions in this graph. Hence it results in a 2D graph with daylight factor and U-value plotted along the X and Y axis and the third dimension of cost indicated with colour coding. For the purpose of comparison, six solutions are picked from the Pareto front and compared against each other on their performance. Table 2 compares the values of the various performance criteria of these 6 solutions. But as suggested by Caldas and Rocha (2001), these solutions must not be interpreted as optimal answers, but as diagnoses of potential problems and as suggestions for further architectural explorations.

TABLE 2. Comparison of evaluation criteria for the 6 selected solutions of Experiment A.

Name of solutions	Average daylight factor (%)	Average U-value (W/m2k)	Cost (k-Euros)	Score for height	Score for sun hours
Solution A	14.75%	0.92	129	2/5	5/5
Solution B	13.75%	0.87	132	5/5	5/5
Solution C	13.68%	0.86	152	5/5	5/5
Solution D	11.45%	0.87	157	5/5	5/5
Solution E	10.92%	0.90	158	5/5	5/5
Solution F	10.53%	0.94	172	3/5	5/5

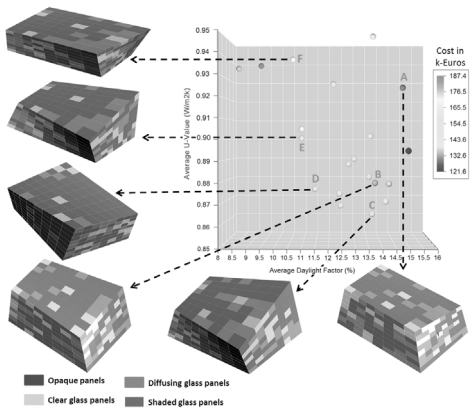


Figure 4. Experiment A – Study of Pareto optimal solutions.

5. Experiment B

In the second experiment, parameters related to the panel configuration and internal floor plan layout are varied along with the panel types.

5.1. DEVELOPMENTAL PROCEDURE

The geometry of the building is maintained as a 12 m × 20 m × 8 m (constant height) parallelepiped shaped space as in Shea et al. (2006). In this experiment, the parameters that define the phenotype are the panels and the movement and rotation of gallery walls in the floor plan as shown in Figure 5.

In this experiment, the panelled roof and the two panelled walls are divided into 1 m × 1 m panels, thereby yielding a total of 496 panels, each of which can be assigned a different material as indicated in Table 1.

The positioning of the two internal partitions defines two spaces: the space between these partitions and the solid walls is the gallery space, and the space between these partitions and the panelled walls is the office space. (The office space combines the office area, meeting area and reception area.) Paintings/artefacts may be hung either on the solid walls or the side of the partition facing the solid wall. Both partitions can move in X and Y directions within the available floor plate of 20 m × 12 m, and can be rotated to a maximum of 90 degrees. In order to avoid generating overlapping partitions, the second partition is actually positioned relative to the first partition. The 90 degree limitation to the rotation ensures that the two partitions always face the solid walls. However for a given position of the gallery walls, there are 2 methods of partitioning the internal space as shown in Figure 5. The method that results in the desired ratio of partition of office and gallery areas is chosen.

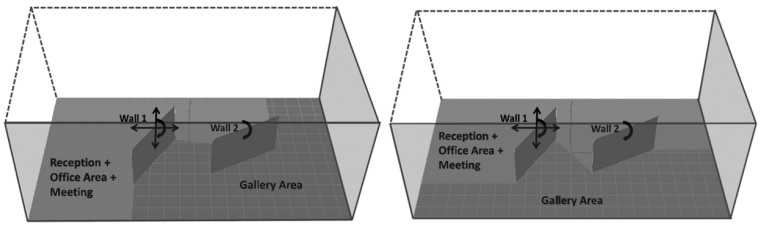


Figure 5. Movement of gallery walls and the 2 methods of area partitioning.

5.2. EVALUATION PROCEDURE

The overall optimisation strategy is the same as Experiment A except that the fifth criterion in this experiment is to achieve desired ratio of floor area between office space and gallery space. The desired ratio of partition of office and gallery areas is specified in the evaluation procedure.

5.3. ANALYSIS OF RESULTS

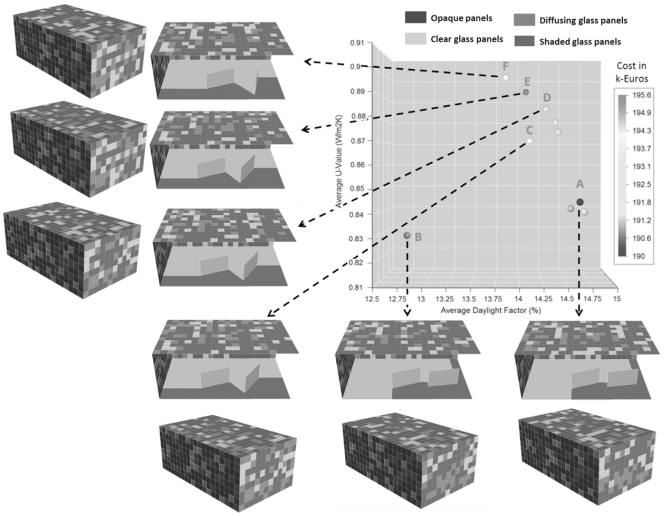
The 10,000 solutions generated for this experiment are analyzed in 3D graphs and a set of solutions are picked from the Pareto Front and are compared

against each other on their performance. Figure 6 indicates both the internal functional space arrangement and the external panel configuration for each of the six selected solutions. Table 3 compares the values of the various performance criteria of these 6 solutions.

TABLE 3. Comparison of evaluation criteria for the 6 selected solutions of Experiment B.

Name of solutions	Average daylight factor (%)	Average U-value (W/m2k)	Cost (k-Euros)	Score for area	Score for sun hours
Solution A	14.61%	0.84	190	3/4	4/4
Solution B	12.82%	0.83	191	3/4	4/4
Solution C	14.10%	0.87	194	4/4	4/4
Solution D	14.30%	0.88	193	4/4	4/4
Solution E	14.10%	0.89	195	4/4	4/4
Solution F	13.85%	0.90	194	4/4	4/4

Figure 6. Experiment B – Study of Pareto optimal solutions.



6. Conclusions

The experiments considered both geometry and floor plan based variations to a panelled building envelope scenario presented by Shea et al. (2006). Experiment-1 evolved solutions with envelopes that opened up to daylight in certain parts and were self-shading in certain other parts of the building, thereby minimizing the use of costlier panel types. (It was noted that the

actual cost of constructing such a façade may be higher due to the complexity of the geometry.) Experiment-2 evolved solutions with better internal functional space efficiency for the same performance goals. The two experiments demonstrate how designers can apply evolutionary techniques to explore differing combinations of design parameters and performance criteria early in the design process during the conceptual stages. The VDM approach within Houdini allowed complex developmental and evaluation procedures to be developed without any advanced programming skills. The Dexen evolutionary system then allowed designers to setup and run advanced evolutionary design explorations.

However, searching through the design variants within the archived evolutionary data in order to make informed decisions was challenging due to both the quantity and complexity of the data. When comparing solutions with more than two performance criteria, it became difficult to visualize the strength of each solution over the other. Alternative approaches that could be explored include parallel projections, spider diagrams, and 3D and 4D graphs.

The experiments have demonstrated how designers could apply evolutionary algorithms to explore a wide range of design variants at early conceptual stages of design process. Future research will focus on developing an improved decision support system for analysing the archived evolutionary data.

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DESIGNING A PERFORMANCE-ORIENTED HOUSE ENVELOPE BASED ON A PARAMETRIC APPROACH

An integrated method

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Abstract. Conventional house envelope design methods often generate few alternatives related to meeting living comfort and building environmental requirements. However, these design methods are increasingly facing difficulties in following the dynamic climate change and advanced building performance conditions in the early stage of the design process. This paper attempts to introduce an integrated method for designing a performance-orientated house envelope in New Zealand which adopts the parametric approach. This approach can guide and assist designers to make a well-informed decision, which can satisfy both aesthetics and energy performance, and gain more efficiency for the design process in the early stage of housing performance simulation.

Keywords. Performance-oriented house envelope design; integrated parametric design; dynamic approach.

1. Introduction

House envelope design strategies have been given increasing attention over the last several decades. Conventional building envelope design methods always produce a small number of design alternatives. As a result, the related environmental evaluation and justification for the house envelope design has been somehow separated from the early design phases in the whole process. In practice, performance simulation is normally postponed to a later stage, which largely limits the success of the design process (Chong et al. 2009). Chong et al. conclude that "in the earlier design stage, assessing the fulfilment of design requirements relies on the insight of the designer who can focus only on a

limited range of performances". It can be seen that these methods are increasingly facing the difficulties of meeting the dynamic nature of performance-oriented design (Turrin et al. 2011, Bechthold et al. 2011).

An early integration of the envelope design needs to be considered as an integral part of the whole process. As CAD/CAM gained its popularity, the parametric design approach (being flexible in nature) has been demonstrated to have complex form-making capacity. However, few have studied this integration approach (Guzik 2010). Due to the underdevelopment of the tools evaluating multiple options, with so many variables in different platforms it is still a time-consuming process. The possibility of a dynamic design system therefore emerged as a field of research for buildings. This paper attempts to introduce an integrated method of parametric approach for producing a performance-orientated house envelope in New Zealand. This research is intended to suggest an emerging design strategy for developing a dynamic envelope panelling system that is to satisfy both the visual form and energy performance. The research scope of this paper is limited and specific on study of performance-based New Zealand house envelope design. The integrated parametric approach for energy simulation is mainly focused. It is noted that this paper is just a starting part of the whole research. There is a growing need for parametric design tools that integrate energy performance feedback in the early architectural design phase (Turrin et al. 2011) to assist designers with well-informed decision-making. A real-time feedback loop between the adjustable geometric properties (windows, insulation and thermal mass) of a house envelope and its corresponding energy performance can be established and evaluated within one unified system.

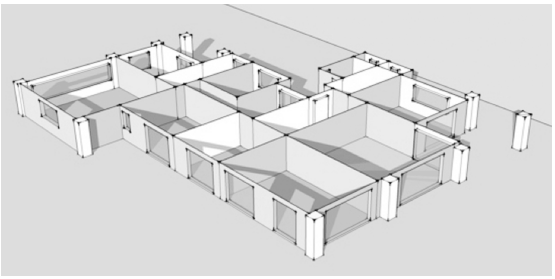

Figure 1. Sketch of the original model

This paper describes the integrated method through the research of a case study, a one level simple house in New Zealand, based on a New Zealand template house which is defined in the book *Designing Comfortable Homes* (Donn 2010) (Figure 1). It is north-facing, 200 square metres, including four bedrooms and two bathrooms. House envelope design is selected to be

explored as the starting point in this research because the building envelope plays a critical part in designing energy-efficient buildings. It functions as an energy mediator between its interior life and the environment of the external world (Lovell 2009).

2. Discrepancy between performance and geometry design

Discrepancy in the whole design process which, including performance and geometry aspects, is explored from the literature review.

A performance-oriented design plays a significant part in designing energy efficient homes in New Zealand. The book, *Designing Comfortable Homes*, established a passive design guideline for New Zealand houses based on the three most important performance factors, namely, glass, mass and insulation (Donn 2010). Glass is to collect the sun's heat; insulation is to keep the heat in; and mass is to store the heat (Donn 2010, p. 6). The three factors are tightly interconnected as each factor is dynamically influenced by the others. For example, in the day-time a bigger window contributes to more heat gain, while at night-time it causes heat loss due to its low R-value.

However, it is often difficult even for the well-intentioned designer to include such a dynamic relationship into the design process (Oxman 2008). As common practice, the fulfilment of code-compliance is the main agenda of performance-based house envelope design in New Zealand. It lacks a holistic approach for designers to design more comfortable homes (Bates and Kane 2009). The current approach has long been recognised as increasingly inefficient in meeting the dynamics of the external climate. For example, there were 27 separated simulation models in Donn's research (2010) in which a very complex process was evolved in order to calculate every possible combination between glass, insulation and mass for a single house.

Furthermore, feedback on the performance implications of design choices is normally lacking in the early stages of the design process due to tools and process limitation (Turrin et al. 2011). Considering the impact decisions made during the conceptual stage on the success of design solution, performance improvements need to be made in the early stages of design process when the building's orientation, thermal mass, materials of envelope, building systems and their properties are proposed (Turrin et al. 2011).

A dynamic system of building design is needed, particularly in the initial stage of the design process where more design options are explored and analysed with the optimised energy design scheme (Toth et al. 2011). The establishment of a feedback loop between form and performance can assist designers to make well-informed design decisions.

3. Performance-based parametric design approach

As discussed above, parametric modelling has the potential of integrating performance requirements into the house envelope design at the early stage. It can represent both geometric entities and their relationships, based on the associative geometry in a hierarchical chain of dependencies.

Parametric design, or parametric modelling, is based on the concept of rules, constraints and association between parameters. All properties of a model, or an object in a model, can be controlled through data values and numbers based on a mathematical formula (Davis 2010). The rules, or numeric values, may represent environmental data (such as solar radiation, solar angles and wind velocity), but as well many other important building geometrical properties (for example cladding panels, sizes and proportions of windows). For design disciplines the concept of parametric has been associated more generally to the notion of design variation (Hudson 2009).

Computational tools such as Maya, Grasshopper, CATIA and Bentley's Generative Components are examples of platforms that allow parametric control of model geometry through parameters and constraints. Currently, the concept of performance-oriented (also called performative) design has recently emerged, as a design method in which building performance is seen as a design driver to guide the whole design process from its inception to final completion.

The house envelope design needs to work as a holistic system to interact with the energy flows in order to create a comfortable living environment and reduce energy use of the building. It is not merely seen as a physical boundary to separate the inside and outside, but increasingly considered as a possibility for integration in a coordinated response to the issue of light, heat gain and heat loss through a dynamic design strategy.

4. An integrated method of parametric design approach

4.1. OVERVIEW

This research provides an integrated method of parametric design approach, which connects house envelope design to building performance (Figure 2). In the early design stage, performance parameters and geometry parameters are cross-examined though establishing governing models and processing models of the original house (details are explained in Stage Two and Three). Such a system enables design schemes to be easily modified in the development and detail design stages, due to its dynamic nature.

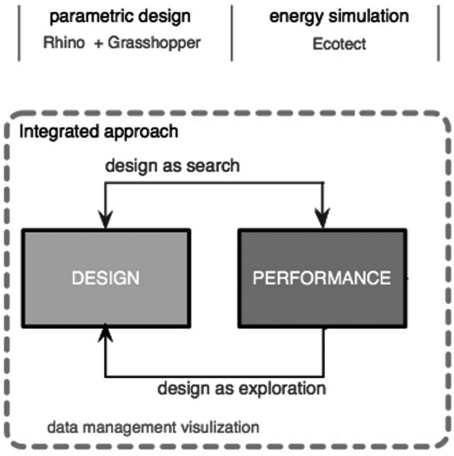

Figure 2. Overview of the method

4.2. STAGES OF METHOD

4.2.1. Stage one: define parameters and constraints

To ensure a common understanding of house envelope design across different platforms (parametric design, performance), a collection of key performance parameters is identified and defined in line with its corresponding geometrical as well as system constraints. Due to the wide breadth of performance-based design knowledge, the proposed system has to be defined in a way that is both specific and comprehensive. The working system boundary is defined based on two groups of parameters, as shown in Table 1.

Two categories of parameters are identified as critical components for the proposed performance-oriented parametric system, namely, performance parameters and geometric parameters. The reason for the selection is discussed in Section 2. In this research, performance criteria to be evaluated are listed, including daylight factors and levels, incident solar radiation, shadow and reflections, and thermal performance (heating and cooling loads).

By assigning different values to glass, insulation and thermal mass, the values of the above performance factors are accordingly adjusted in parallel with the geometrical change of the house envelope. The change of performance factors can be visualised within the system, which assists designers to make possible the interaction between design selections and their energetic impact.

TABLE 1. Different types of parameters

Types of parameters	Parameters	Values		
Energy parameters [1]	Glass (wall WWR)	25%	40%	55%
	Insulation	Code	Better	Best
	Thermal mass	Low	Medium	High
	Orientation	Floating value		
	Solar azimuth and altitude	Floating value		
	Location	Wellington (fixed)		
Geometry parameters	Window unit size	Floating value (w×h)		
	Window distribution types	Floating value (n)		
	Wall (panel) grid	Incremental values (u×v)		
	Wall inclination angle	Floating values (d)		
	Wall curvature factor	Dependence on grid points		

[1] Key parameters as have been identified as necessary in constructing an early energy model for house envelope design (Donn, 2010).

Grasshopper is to be selected for the parametric modelling tool because of its gaining popularity in research and practice and its seamless integration with Rhino, which offers capacity of flexible modelling, rendering and design work flow. Autodesk Ecotect, an energy performance simulation tool, is selected for this research because it offers a wide range of simulation tasks and is broadly used both in research and practice.

4.2.2. Stage two: parametric governing model

Stage Two establishes a governing model based on the original model (from Donn 2010) – this model has been introduced in the early section. It is a surface-based model composed of geometric primitives (points, polygons and surface). It is to explore various possibilities of linkage and interaction between parameters though a series of tests. This stage is principally about taking the parameters defined in Stage One (detailed in Table 1) and relating them to the original model. A flexible relation between geometries and energy performance is analysed. A relational diagram is applied in mapping the full relationship of different parameters. The governing model, then, is established in such a way that it can explicitly manipulate both the geometrical and performance variables for feedback data visualisation and result comparison.

Two tests are undertaken in this stage to explore various aspects of the governing model. Figure 3 shows the schematic diagram of two tests. The various combinations of parameter setting and their interrelationship are examined in these tests. The living room of the “house model” (one thermal zone) is selected and a series of tests are undertaken against some basic environmental criteria:

- Test One explores the visual feedback of performance factors triggered by changes of performance parameters (Details of this test is listed in Table 2).
- Test Two explores the direct visual interaction between geometry and performance. Expected changes of performance results are triggered by various window distribution patterns and wall tilting angles. Test Two is based on the governing model from Test One (Details of this test is listed in Table 3).

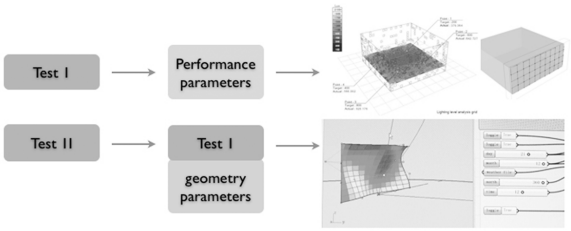

Figure 3. Schematic model of two tests in Stage Two

TABLE 2. Details of Test One

Input	Performance parameters (insulation, glass, thermal mass, orientation, sun path)
Process	Explore the visual feedback of performance factors triggered by changes of performance parameters
Output	Data visualisation within the governing model system (daylight factors and levels, shadow diagrams, incident solar radiation)
Steps	• Translating specification from constraints defined in Stage One to relational schema (diagram) for one thermal zone • Explore various parameter combinations by changing several levels of performance parameters (including glass, insulation, mass)

TABLE 3. Details of Test Two

Input	Geometry parameters + performance parameters
Process	Explores the direct visual interaction between geometry and performance
Output	Design iterations with various geometry properties and performance data
Steps	• Modify the original model in a visually interactive way. Geometries of the house envelope is synchronised with performance criteria (for example changing size of windows can directly impact on daylight availability) • Examine the feedback loop between geometrical forms and their performance

4.2.3. Stage three: processing model: design exploration, simulation and visualisation

Stage Three is a core component of the overall research. It focuses on the full range of performance requirements (explained in Stage One) with multiple thermal zones in terms of surface subdivision.

Simulations are run for winter and summer scenarios respectively; the objectives of the optimisation are different between winter and summer. In winter, it is aimed at maximising both the daylight factor and incident solar radiation; in summer it needs to maximise the daylight factor, but minimise incident solar radiation. The conflicting objectives pose challenges for design exploration. The combination of monthly incident radiation (June and December) and daylight factors are set as performance goals for generating a large collection of corresponding geometric iterations of the envelope. The Galapagos, a plug-in of Rhino Grasshopper, is applied as a bi-directional approach aimed at tackling the multiple-objectives problem.

Based on the parametric "governing model" from Stage Two, Stage Three is to develop a processing model, which takes one step further from Stage Two (single objective in single thermal zone) towards multiple objectives in multiple thermal zones (Figure 4 and Table 5).

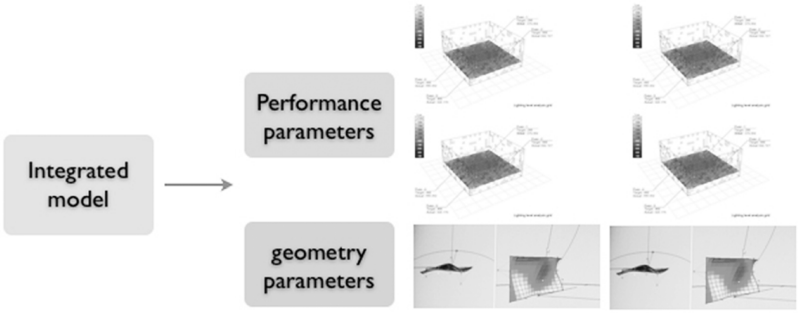

Figure 4. Schematic model of Stage Three

TABLE 5. Steps of Stage Three

Step 1	Refining the governing model by including three groups of parameters (allow grid points movement in different directions within a given range)
Step 2	Assigning the cladding panels and glazing in Rhino and setting up platform
Step 3	Analysing and sorting the solution of fitness towards which design iterations can automatically be compared and optimised

Step 4	Automatically computing the process of searching and generating envelope geometry towards the fitness goal through the working platform; two collections of design iterations (winter and summer) are expected
Step 5	Envelope surfaces are subdivided according to assigned material constraints
Step 6	Manually analysing the outcome of geometric forms, performance data
Step 7	Setting up a database to store collection of data of design iterations; a web server is to be established at www.parametrichouse.com to host the database that will be later applied for visualised tests

5. Conclusion

This paper attempts to establish an integrated method of a parametric design approach for performance-orientated house envelope design. This approach is to assist designers to make a well-informed decision to satisfy both aesthetics and energy performance requirements, and to gain more efficiency for the design process of performance simulation in the early stage.

It found that there is a growing need for parametric design tools which can assist designers with well-informed decision-making. The advancement of Computer Aid Design (CAD) in the building industry, particularly the recent development of parametric design combined with other energy simulation tools, promises some possible directions to create and build a building envelope with complex geometry and climate-oriented adjustment in form. It provides a flexible system containing associative parameters with adjustable values. It can be explored during design through variations of performance-related parameters that meet the internal and external climate conditions.

Currently, this research investigates a conceptual view of the dynamic approach to provide a foundation for improving the understanding of house envelope design across different platforms (parametric design, energy performance). This paper is just a starting point. This whole study is intended to fill the gap for a theoretical system between the architectural, performative processes.

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A RESPONSIVE MORPHING MEDIA SKIN

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Abstract. Existing media façades do not function as fenestration devices. They have been used mainly for visual communication and aesthetic purposes. This paper introduces a responsive morphing skin that can act as an active fenestration device as well as a media skin. We investigate new possibilities of using form-changing materials in designing responsive morphing skins that respond to environmental conditions and act as a communicative display. The design experiment that embodied this investigation, namely *Blind*, serves as a new layer of analogue media brise-soleil for existing space. It communicates the relationships between interior and exterior spaces visually and projects mutable imageries to the surrounding environment through sunlight. The design process of *Blind* simulates the responsive behaviour of the intended architectural skin by integrating physical computing and parametric design tools. This process includes the integration of soft apertures and architectural morphing skin to introduce a novel design method that enables an architectural skin to be a means of communication and fenestration. It responds to changing stimuli and intends to improve the spatial quality of existing environments through two types of transformations: *morphological* and *patterned*.

Keywords. Media façades; elasticity; responsive architecture; form-changing materials; kinetic skin.

1. Introduction

The rising popularity of designing media façades using LED, fluorescent lighting and projection technology in contemporary architecture is attributed to the increasing accessibility of such technologies. The BIX façade in the Kunsthaus Graz in Austria is the significant precedent of these approaches (Elder and Elder 2003). The GreenPix media screen at Beijing designed by Simone Giostra & Partners with Arup is another salient example that involves

the use of conventional LED displays for communication and social interaction purposes (GreenPix 2008). However, there are no existing media façades that have been co-utilised as a fenestration device. Permeability properties of an architectural skin that allows moderation between the interior and exterior conditions can be used as a key consideration for designing a media skin. What if a media skin with permeability features can perform similar visual effect to the conventional media screens?

The recently completed Media-ICT building designed by Cloud 9 Architects in Barcelona demonstrates an energy efficient architectural skin that uses soft materials as part of the visual display. The *soft* façade made of ETFE responds to the user needs. The ETFE skin protects the interior by regulating indoor climate from direct sunlight. When more light is needed, the pneumatic skin deflated to let the daylight in (Ruiz-Geli 2011). This pneumatic kinetic shading device sets an early inspiration to conduct this research work; however, further investigation is needed especially in terms of allowing air ventilation and shadow casting of media skins. Another precedent is the project *'ShapeShift'* which uses an assembly of kinetic membranes using EAPs (electro active polymers) to prototype robotically fabricated room-dividers (Kretzer 2011). However, this prototype needs extremely high energy for transformation and lack of representation of any media contents.

The design exploration presented in this paper investigates the *morphing* aspect of the 'soft' kinetic architectural skin to perform visual communication effect without using LED digital display. In the field of engineering, the word morphing is used when referring to continuous shape change, for instance, no discrete parts are moved relative to each other but one entity deforms upon actuation (Thill et al. 2008). The term *morphing* is used in this research to describe the use of form-changing materials to perform kinetic actuations on responsive skins with little use of mechanical components. In contrast to other kinetic or media façade projects, this research investigates new possibilities of attributing *softness* and *elasticity* in form-changing material system that applies to an architectural skin. It also responds to environmental stimuli and act as a communicative display. The passive and active form-changing materials such as silicone rubber and shape memory alloy (SMA) are used to test these new possibilities. The simple, thin and lightweight design of the *architectural morphing skin* (AMS) provides an economical alternative to the conventional digital media surface by adding inherent potential functions to regulate ventilation and sunlight.

The study of this research intends to expand the repertoire of current responsive digital media skins design by developing an alternative method for architects and designers to integrate form-changing materials with com-

putational processes to design a responsive morphing media skin. It aims to explore the passive and active design strategies integrated parametric design tools and contemporary sensor devices.

2. Soft responsive kinetic system

There are possibilities for implementing the *soft responsive kinetic system* (SRKS) in physically responsive architectural morphing skin (AMS) in this research. This system provides a platform to shift from hard to soft material system approaches for designing architectural media brise-soliel. It also develops an appropriative method for studying soft responsive morphing skin that improves the quality of our design explorations. Instead of inventing systems or synthetic materials, we shift the approach to exploitation of existing form-changing materials that have been applied in other disciplines but are new in the context of this architectural vision. The kinetic actuation of SRKS does not require the use of mechanical components, pistons or motors. Instead the overall system uses form-changing materials for actuation purposes. SRKS served as a proposed system for designing *Blind,* a design exploration for morphing media brise-soleil discussed in Section 3. It is also a novel design method of inquiry which included four elements, *Skin*, *Skeleton*, *Actuator* and *Sensor* for their individual design strategy and implementation (Table 1).

TABLE 1. Elements, design strategies and implementations of Soft Responsive Kinetic System (SRKS).

Elements	Design Strategies	Implementations
Skin	Elasticity	Flexible
Skeleton	Tensegrity	Transformation
Actuator	Form-changing materials	Actuation
Sensor	Adaptability	Sensing

The design strategy of the *Skin* element of the SRKS focuses on elasticity to produce flexible *architectural skin*. Elastic materials deform when force is applied and the deformation is reversed once the force is removed, returning the materials to the original state. The potential energy stored within the material itself can be harnessed to activate the deformation process back to its original state. This offers potential new forms of flexibility, adaptability and deformation using the memory effect in architectural skins. The elastic material used for the design exploration is silicone rubber given its durability, heat resistance and elastic capacity. The heat tolerant material property makes silicone rubber a suitable material to integrate with active form-changing

materials (SMAs) to form a morphing skin, addressing elasticity and actuation respectively (Figure 1).

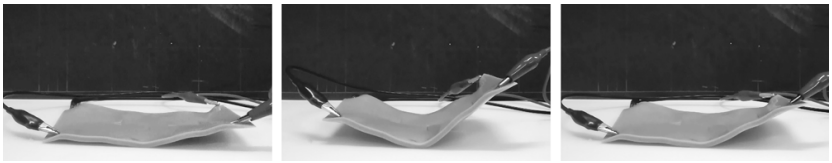

Figure 1. Early experiment for elastic silicone rubber skins set as the elastic component and actuator by electric stimuli.

The *skeleton* element of SRKS focuses on the tensegrity structural approach that reduces the friction between mechanical joints and achieves a lightweight structure. Due to the interdependent nature of all the elements, a slight change in any of their parameters can result in a significant form transformation (Fumar and Zhou 2009). For these reasons the tensegrity *skeleton* was chosen as part of the SRKS and for its flexibility and lightweight components. The lightweight accessible ABS (Acrylonitrile Butadiene Styrene) used as the primary strong explicit materials to fabricate tetrahedral modular components integrated with stainless steel coated wires. Eventually they form the light weight and flexible tensegrity tetrahedral modular skeleton as the exoskeleton structural system of *Blind* (Figure 2).

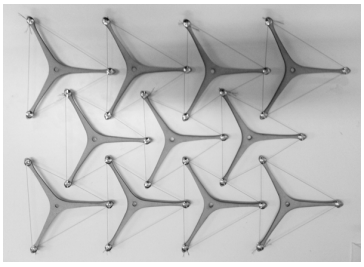

Figure 2. 'Simplified' version of tetrahedral modular skeleton.

The *actuator* element of SRKS addresses the use of active form-changing materials for *actuation* of the SRKS. We proposed the use of shape memory alloys (SMAs) as the active form-changing materials to investigate the alternative of actuation, since the dynamic deformation, expansion and contraction, of SRKS can be achieved and controlled with electrical stimuli. The deformation of SMAs occurs under electrical stimuli using 5 V for a 1.5 amp current to perform potential actuation (Figure 3). The four potential profiles for this 'soft' actuation based on the process of expansion and contraction in

specific parts of the SMA wires discussed in authors' previous work (Khoo et al. 2011).

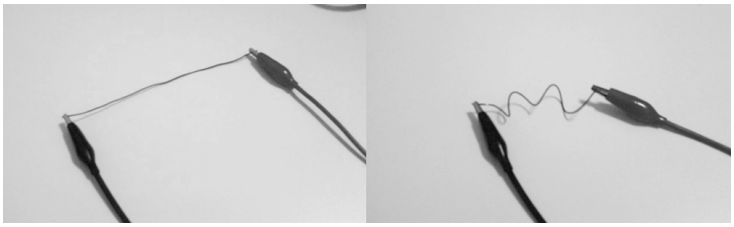

Figure 3. Deformation of SMA wire occurred when heated by electric stimuli.

The *sensor* element explores the adaptability of SRKS in order to achieve morphing skins that display elastic properties, and respond to digital and physical stimuli. This idea is developed using parametric design tools discussed subsequently in Section 3. The application of *Blind* is as a prototypical kinetic shading device and media screen with sensing ability that to regulate shading and visual effect. It aims to improve the comfort level as well as visual communication between the exterior and interior of spaces. This application embodies in an experimental process used design tools such as Grasshopper and Firefly parametric software together with Arduino microcontroller and photo resistor (Figure 4). The integration of these open source software and hardware make initial digital simulation and physical experiments possible.

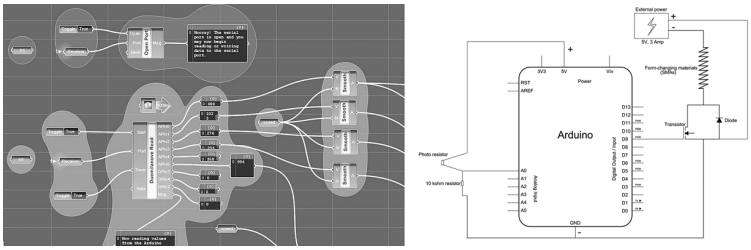

Figure 4. Left: Grasshopper and FireFly parametric schema. Right: diagram of adaptive process of SMA control through Arduino microcontroller with physical computing.

3. Design exploration

The design exploration of the responsive architectural morphing skin through soft kinetic system, called *Blind,* is presented in this section. *Blind* serves as the *analogue media brise-soliel* to display binary images and motion graphics using the perforation process of the soft surface composed by the *'eye-like'* permeable apertures. The '*analogue pixels'* of the surface creates a new layer

of visual intervention in the form of responsive semi-ellipsoid canopy to allow communication between the ambient environment and the *Blind.*

Blind is a multilayer architectural morphing skin that composed by two types of triangulated modules (Figure 5). It manipulates sunlight through bending and twisting of its undulating surface. This malleable fenestration through the input of real-time data constantly cast controlled shadows over the surface under its semi-ellipsoid canopy (Figure 6). The shadow casted into the existing surface through this process provides a morphing atmosphere that suggests a continued relationship between exterior and interior space. The conventional digital media screen, in comparison, lacks the consideration of its effect on the interior condition.

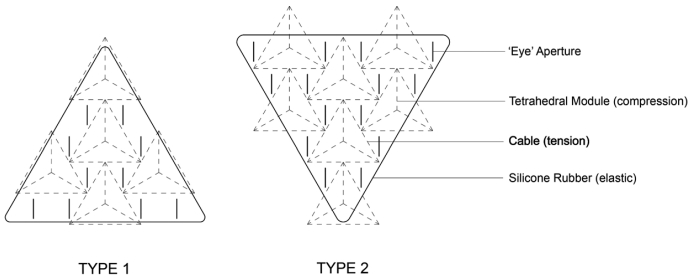

Figure 5. Two typical types of triangulated modular skin embedded with tensegrity tetrahedral components.

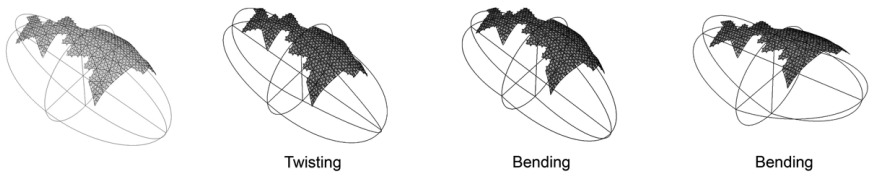

Figure 6. Blind in the form of semi-ellipsoid canopy performed morphological transformation for optimal sunlight manipulation through bending and twisting.

Blind includes two types of transformations that respond enable adaptive visual effects and media communications: *Morphological* and *Patterned* (Figure 7). Morphological transformation is a *global* morphing process of the entire undulating skin structure to control shadows casting and lighting manipulation for various visual effects of space under *Blind*. Patterned transformation involves *local* individual openings that are opened and closed to serve simultaneously as *'analogue pixels'* and as apertures.

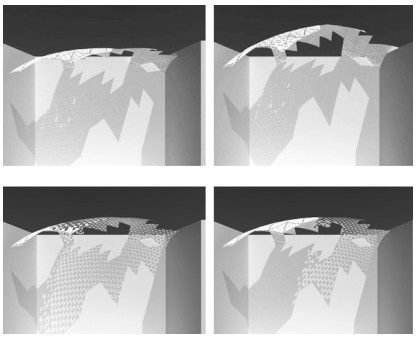

Figure 7. Above: Shadow casting by global morphological transformation. Bottom: Projected domestic morphing shadow and light spot patterns of patterned transformation.

3.1. MORPHOLOGICAL TRANSFORMATION

Morphological transformation explores the global surface curvature of *Blind* to be modifiable while maintains the continuous topology of undulating or flat surface. It responds to various functional drivers to manipulate the lighting effects in global scale. This morphological transformation demonstrates an alternative actuation system using SMA springs integrated with the overall tensegrity structures as discussed in Section 2. The global actuation takes place in between the tetrahedral skeletons and skins and is triggered by the contraction and expansion of the SMA springs through electrical stimuli (Figure 8).

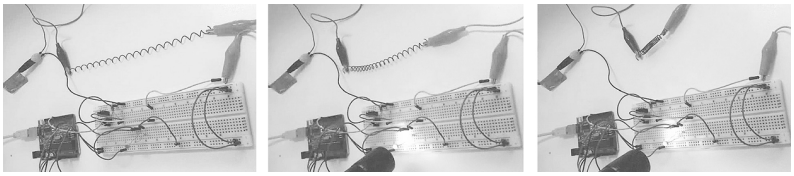

Figure 8. SMA spring responds to direct light through a photo resistor to perform contract and expand actuation.

The adaptability for morphological transformation process of *Blind* is tested by using a photo resistor as light sensor and the torchlight mimicking the path of sunlight to embody the initial global transformation of physical responsive triangulated modular skin (Figure 9). It responds with various morphological states for optimal visual performance as a direct sunlight modulator that creates multiple lighting effects. This global morphing process constantly redefines the face or image of the existing building environment in order to materialise *Blind* as a media brise-soliel as well as responsive intervention.

This process also allows *Blind* to serve as a new transformable visual barrier in between interior and exterior spaces that have been overlooked in conventional digital media façades.

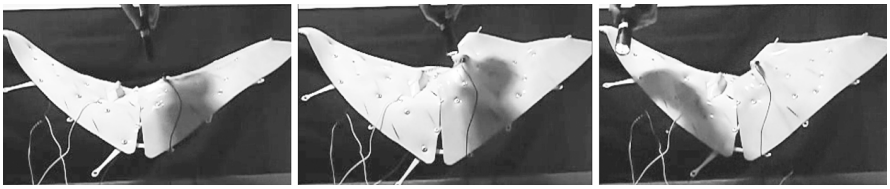

Figure 9. Morphological transformation of two types of physical triangulated modules of Blind responding to direct light for optimal visual performance.

3.2. PATTERNED TRANSFORMATION

The patterned transformation through permeability of *Blind* is generated by the individual domestic 'soft' apertures as *analogue pixels* projecting light spots in response to sunlight penetration. This transformation manipulates the spatial conditions of the interior and exterior spaces through the dynamic patterns of the skin surface. The initial geometry of the membrane aperture is inspired by the performance of the eye. The *'eye-like'* apertures in the geometry are determined by their relative curvature on the responsive undulating silicone rubber surfaces and actuated by SMA wires and springs. This analogy of an *'eye-like'* permeable aperture functions as a skin muscle mechanism in the eye which allows various changing porous patterns in binary form on the skin (Figure 10). This perforation process created a potential application for the surface of *blind* as the *analogue media brise-soleil*, to display binary images or even motion graphics.

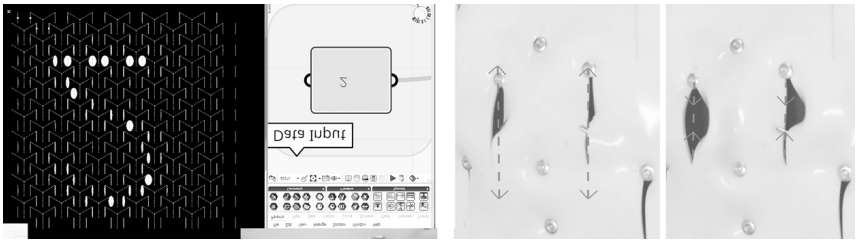

Figure 10. Left: Digital simulation of Light spots fenestration through 'eye' apertures formed numeric texts and textual visual patterns. Right: Physical domestic 'eye-like' apertures open and close actuated by embedded SMA wires.

The patterned transformation process of *Blind* adds a new layer of aesthetic for visual communication between existing space and external surrounding environment. This visual intervention demonstrated in a digital simulation creates a new media skin for communication between the existing spatial and the surrounding environment through its constant malleable porosity activated by real-time input data (Figure 10). The exterior skin of *Blind* allows light penetrates the 'eye' apertures to form the numeric texts light spots projected on the surface underneath *Blind*. Other textual visual patterns also formed by the light spots penetrating through the 'eye' apertures.

The fenestration of patterned transformation also performs the motion graphic representation in an analogue manner. The actuation of the 'eye' apertures of *Blind* occurs in two states, 'open' and 'close'. This produces an animated *'shadow play'*, which is an illusion of still and animating images caused by the illumination of the *Blind* under the sunlight. This real-time '*shadow play'* creates, potentially, a 3D volumetric analogue cinematic interior environment that responds to changeable events. The patterned transformation allows *Blind* to become a projective device by controlling direct sunlight and artificial lights penetration using real-time input data. This process extends the cinematic ability of conventional shadow play but in an architectural context.

4. Conclusion and future work

Architectural skins have become the interface of buildings in their surrounding urban environments. In general, these architectural devices serve as the building 'billboards' which normally serve as a one-way information communicator. The digital screens of these 'billboards', or more commonly referred to as media façades, often neglect the interaction between the interior and exterior conditions, especially in terms of moderating visual effect and lighting fenestration to the interior space.

We investigate the new potential designing responsive architectural media skins without digital display to achieve visual communication effect using 'soft' active and passive form-changing materials embedded in a tensegrity structure. This approach demonstrates a new method to extend the design of architectural media skins with environmental design considerations, particularly for moderating light in the interior spaces. It is also integrated with physical computing and parametric design tools to form a responsive kinetic system for simulating the comprehensive physical media display prototype.

Future work includes designing and developing a new Architectural Morphing Skin (AMS) that is able to perform sensing, analysis and actuation in one solid-state responsive entity, and installing a full-scale AMS at an urban site for practical architectural applications.

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SPHERE MAPPING

A method for a responsive surface rationalisation

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Abstract. The method proposed in this project addresses the parametric manipulation of a given pattern to respond directly to a pre-defined surface. Continuing the research of Kevin Rotheroe, Yale University and founder of FreeForm Design. Rotheroe has developed a series of studies in material and surface properties. By utilising a proven pattern, the proposed method sets parameters derived from the formal properties of the original pattern and produces a new pattern that is responsive to the curvature of a complex surface. The workflow developed in this research consists of a complex blending of tools in Grasshopper and Gehry Technologies Digital Project. The intent is to achieve the aesthetics and structure offered by Rotheroe's original research and to add a responsive precision that provides an accurate adaptation of the pattern based on curvature of a specific computationally defined surface.

Keywords. Geometric systems; parametrics; material constraints.

1. Introduction

The exploration of adaptable surfaces in the field of architectural research is pertinent to elements such as façades, building skins, and interior façade surfaces. It allows a single pattern to be applied to any given surface within a building while responding to the constraints of those surfaces. Parametric software has made complex structural systems tangible and doubly curved surfaces feasible. Rotheroe (2001a) investigated patterns and the various methods of construction (see Figure 1), which release materials into plastic bent forms. The surfaces produced address material and production constraints, pattern

study, and modelling processes. The studies focus on the purity of the patterns and their limits. The intent of following research is to extend the research is to test a parametric model that rationalises a tessellation patterns as a response to a predefined surface. The proposed method will adapt a pattern to a given surface. In this method, Rotheroe's (2001b) workflow of pattern before surface is reversed, resulting in a pattern that responds directly to a complex surface. Furthermore, the production strategy of subtractive CNC plasma-cutting will be utilised to produce the resulting surface.

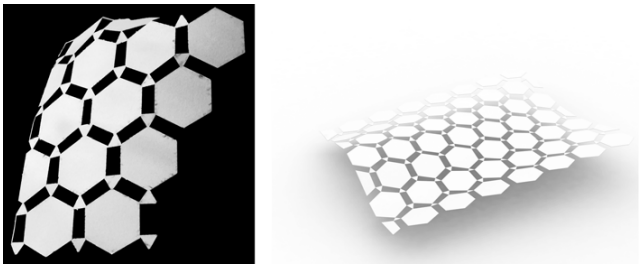

Figure 1. Physical (left) and parametric (right) reproduction of original pattern.

2. Parametric modelling work flow

2.1. SPHERE MAPPING

This version of the process was mapped entirely through geometric relationships in Gehry Technologies, *Digital Project* and *Grasshopper*. In *Digital Project*, the process of Sphere-Mapping is applied to a given surface. This technique creates triangles on the surface by creating spheres that intersect with the surface. To start the process, the pattern and triangles that form the hexagons are laid out two-dimensionally. The triangles provide the radius of the spheres with their dimensions in addition to providing the dimensions the hexagonal shapes (see Figure 2).

Figure 2. Sphere-mapping process in Digital Project. Sphere intersecting with surface (left). Resulting lines projected on surface (centre). Resulting fixed size triangles (right).

In order to map the triangles, two isocurves are created on the surface; one in the 'u' direction and one in the 'v' direction. The intersection of the two isocurves is used as the centre point for the first sphere of the sequence. The sphere and the surface intersect to create a curve on the surface (whose points are all equidistant from the centre of the sphere). To construct the next sphere, the previous steps are repeated with the second radius given by the corresponding triangle of the two-dimensional layout. The point of intersection of the two curves is the first point of the triangle. In this particular pattern, however, there are two sizes of triangles. One set comprises the hexagons while the second set is used for spacing between the hexagons. A triangulated structure is the result of the sequence. The sequence must free itself from the surface, operating in the centre of the form, free to "flow" on the surface as the triangulation necessitates.

3. Surface division

The final workflow involves processes that require the geometric flexibility of tools in *Grasshopper* and the geometric precision and rapid replication provided by *Digital Project*. In this method, *Grasshopper* was to develop a parametric process for linking triangulation sizes or pattern sizes to the twist and radius of the curvature. The intent is to generate a surface to which a pattern can be flexibly applied. In order to achieve a regular partition of the given surface, the "Divide" and "Subsurface" tools are implemented. The result is a surface of triangles of approximately the same size. Next, the "Mesh" command is applied to further divide the partitioned surface into more responsive and articulated triangles. The division produced by "Mesh" tools is affected directly by the curvature of the surface. However, the outcome is not functional until the "Delaunay" tool is applied to subdivide the surface and make the triangle sizes responsive to the radius of the curvature.

"Delaunay Meshes" produce appropriately responsive subdivisions by avoiding the typically thin triangles of conventional meshes. Delaunay meshes by their definition create triangles with the maximum sized angle of the vertices. This creates an idealised form as it minimises the difference between each adjacent triangle.

First, precise changes on the surface were defined that respond to the twist of surface in certain places. Triangles become smaller as the radius of the surface increases. Second, the angle tolerances are controlled to avoid extreme changes in the surface. When a surface curves beyond a certain point, the "Delaunay Mesh" tool divides the area undergoing the relatively extreme radius into smaller triangles. This allows the surface to bend. *Grasshopper* is used to transition into *Digital Project*. The "Mapping" tool makes it possible

to transform all the lines of the curved surface onto a flat surface created by unrolling the original curved surface. The outcomes are precise, however, *Rhinoceros* restricts the use of the unroll command in cases of doubly curved surfaces. Therefore, the responsive surface at this moment is either singly curved or requires stitches between breaks to reconnect splits or slots between zones of the surface.

Application of Pattern to Surface

The decision to move the process to *Digital Project* is validated by the software's ability to apply a pattern iteration to multiple surfaces, producing derivations of the original pattern that respond directly to the new surface. After much exploration, the "power copy" process in *Digital Project* proved to be the most efficient tool for creating the adaptive geometric linkages between Rotheroe's hexagonal pattern and the Delaunay triangulation. The "power copy" process allows a shape to be copied to a separate area of the surface while keeping the original properties of that shape intact. Using the two-dimensional file imported from *Grasshopper,* the points of the existing triangles are used to locate the points of the hexagons. Within this particular pattern, there are two different types of hexagons and three different types of triangle joints. The set of hexagons consist of alternating rows of dominant hexagons and recessive hexagons. The three triangle joints are necessary in order to address the different orientations of the joints. In order to maintain consistency throughout the pattern, a separate "power copy" is necessary for each type of shape (see Figure 3).

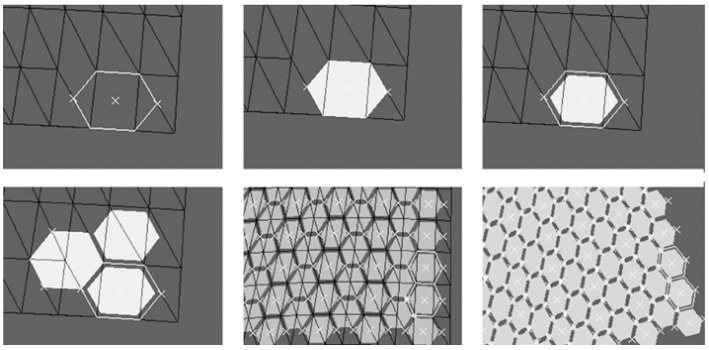

Figure 3. Power copy process.

3.1. POWER COPY PROCESS

Beginning with the main hexagon, six points are located on the triangles of the original mesh to construct a surface. In order to compensate for the spacing

between each hexagon in the original pattern, a copy of the hexagon is scaled down in size. The original hexagon is then hidden. The workflow of *Digital Project* does not allow objects to be erased after a power copy has been made. The copied object is directly linked to the original, and will lose any data if the first shape is deleted. Therefore, in order to simplify what is viewed, the original shape is hidden. To replicate the "power copy", the first hexagon is selected followed by the "Instantiate Form Selection" tool. The resultant new hexagonal surface contains the same properties as the original but responds directly to the points selected. In this phase, the variation in shape and size is evident. To create the proper pattern, each row consists of several of one of the two hexagonal power copies. Each original power copy must be made prior to the replication of shapes.

3.2. PREPARATION OF CUT FILE

The model is now exported as an ".igs" drawing and imported into *Rhinoceros*. We elected to test the subtractive construction method for both the CNC Laser Cutter and CNC Plasma Cutter machines. In order to fit the cut file to a given sheet size, in this case 4'-0" by 8'-0", a box of the given dimension is drawn around the imported drawing. Any hexagons that do not fit onto the sheet are "trimmed" from the drawing. The proportions of each type of cut were matched to the thickness of the material. For chipboard, .022", and for 20 gauge steel- .0359.

The resulting pattern consists of hexagonal shapes, separated by four-sided gaps, and triangles at the connectors. The entire surface consists of planar shapes that bend only at the points where hexagons meet a triangle: there are no curved shapes. The resulting file is the hexagonal pattern that is ready to be cut into the full sheet or scaled down to do mock-ups.

3.3. RADIUS AND CURVATURE ANALYSIS

The analysis of the curvature radius is important in order to understand whether or not the pattern can adhere to the limitations of the material, in this case, 20 gauge steel. The responsive properties include tessellation only on "twist" of the surface. Definition can be changed where the extreme radius of 16" present (see Figure 4). The bent surface at the edge will tessellate (see Figure 5). The change in size of the hexagons is the direct response to the twist of the surface. This explains why that particular portion of the tessellation changes (see Figure 4). Because the hexagons were derived from triangles and do not match the original tessellation exactly, sizes are different but are proportionate to the original curvature of the surface.

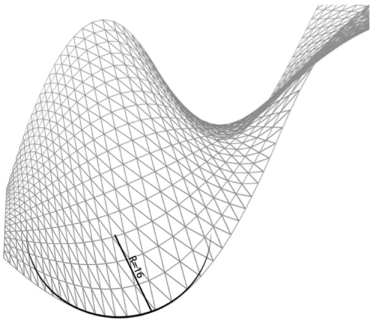

Figure 4. Radius of the curve with changing tessellations.

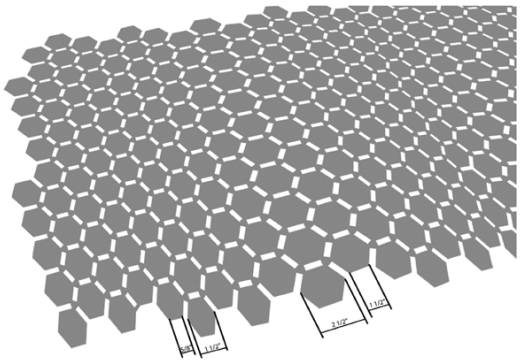

Figure 5. Tessellations (triangles) converted into hexagons have different sizes but are related and proportional to original surface.

4. Mock-up process

Once the cut file is ready, mock up models were generated (see Figure 6). The production of scaled and full size models using materials such as chipboard defined inaccuracies or failures within the pattern. It also afforded us a test to determine whether the *Grasshopper* pattern is physically capable of bending to the surface. After the cut file have been modified according to the chipboard mock-up, we cut a portion of the file from a 20 gauge steel sheet, 2'-0" by 2'-0", on a CNC plasma cutter (see Figures 7 and 8). The egg crate (intersecting contours of surface) made in stage three is cut and assembled to verify the accuracy of the chipboard model and to achieve the accurate mapping of the surface.

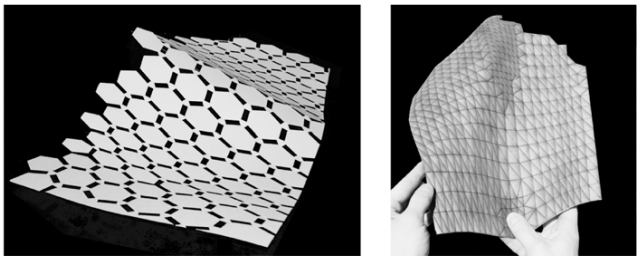

Figure 6. Laser cut chipboard mock up of final pattern and triangle mesh.

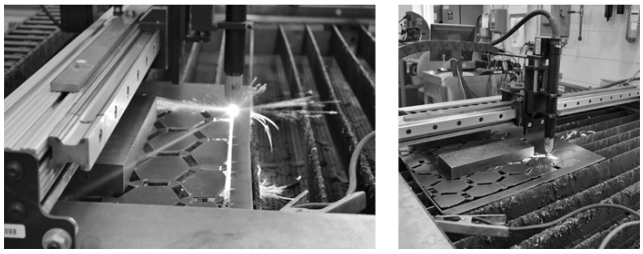

Figure 7. CNC plasma cutting in progress.

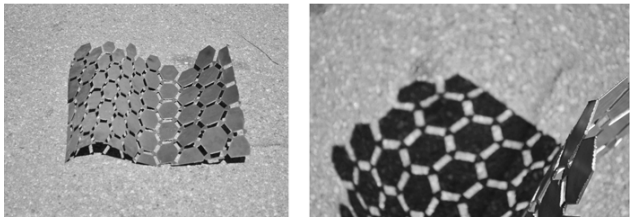

Figure 8. Final test cut.

4.1. EGG CRATE

In order to accurately test the final product, the surface was applied to an egg crate structure. The egg crate was used as a tool to produce an accurate and precise bend of the surface. Using a CNC router, ¾" plywood was cut using a two dimensional drawing arranged onto 4'-0" by 8'-0 boards (see Figure 9).

4.2. FINAL SURFACE

The next phase of the process entailed the use of a CNC plasma cutter to cut 20 gauge steel test sheets. Explorations in this phase include the testing of cut line variations, material property studies the analysis of sheet's ability achieve the proper curvature. The egg crate functions as a guide for the metal. The cut hexagonal sheet will not fit exactly to the egg crate, this is part of the explora-

tion of material/method constraints. The piece is laid over the structure and going from one end to the other is slowly bent to the egg crate. The goal is to form the metal to the egg crate as well as it can until the joints start to stretch and compromise their geometry. This shows us where the constraints of the material and the pattern/method meet.

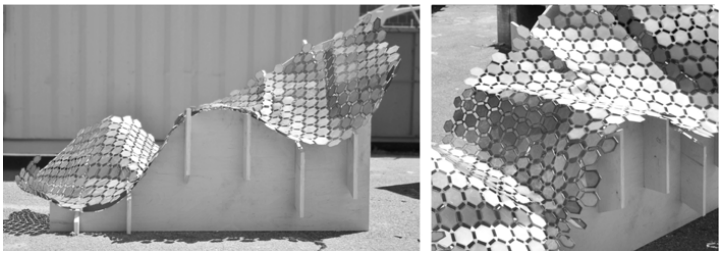

Figure 9. Final surface bent over egg crate.

5. Conclusion

5.1. OVERVIEW

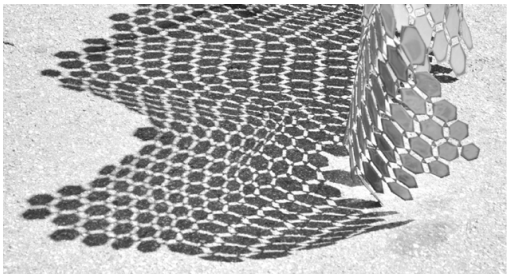

Figure 10. Shadows displaying change in size of hexagonal patterns.

The surface produced proved the proposed method to be successful in several ways. The expectation of creating sub-divisions that correspond directly to the curvature of a given surface were met (see Figure 10). The pattern components varied in size in the desired areas, allowing the metal to take the proper form. The gradual dimension change of the original triangles reciprocated in the transition of hexagons. Overall, the surface adhered to the same aesthetic quality of the original Rotheroe pattern while maintaining structural integrity. The elegance and precision present in the original pattern were actually enhanced through further articulation. The connections proved relatively

strong and provided ample flexibility to support the bending of the metal. The triangles serviced the bending requirements, and alleviated any harsh or drastic bending by the introduction of smaller hexagons in areas of extreme curvature.

5.2. FUTURE WORK

The product of this process is a study to understand the strengths and weaknesses of a responsive pattern system. However, understanding the constraints of the system, the applications became more evident. The ultimate intent was to create a pattern that can respond in size to the complexity of a surface. The current system responds rather well, however, it would benefit from further iterative studies in order to understand the optimum connection for the pattern and material. The process is applicable to the study of other material constraints, which could be defined as responsive to materiality, surface and form.

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PARAMETRIC AND GENERATIVE METHODS WITH BUILDING INFORMATION MODELLING

Connecting BIM with explorative design modelling

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Abstract. Parametric and generative modelling methods are ways in which computer models are made more flexible, and of formalising domain-specific knowledge. At present, no open standard exists for the interchange of parametric and generative information. The Industry Foundation Classes (IFC) which are an open standard for interoperability in building information models is presented as the base for an open standard in parametric modelling. The advantage of allowing parametric and generative representations are that the early design process can allow for more iteration and changes can be implemented quicker than with traditional models. This paper begins with a formal definition of what constitutes to be parametric and generative modelling methods and then proceeds to describe an open standard in which the interchange of components could be implemented. As an illustrative example of generative design, Frazer's 'Reptiles' project from 1968 is reinterpreted.

Keywords. Building information model; parametric modelling; generative modelling.

1. The need for interoperability

With the rise in complexity that has come with contemporary architecture – whether it is to do with the complexity of form, the need for better performance, or facilities management – there is a greater need for tools to help the process. As the number of digital tools we use increases – there is a greater need for interoperability between different applications. Building Information Models are a way of allowing communication between different disciplines by having a semantically rich model to-and-from which data is transferred.

The open standard for building information models is the Industry Foundation Classes (IFC) which is regulated by the IAI (International Alliance for Interoperability). The specification is vendor-neutral and is in the process of becoming International Standard ISO 16739. In this research paper, all Building Information (BIM) models refer to IFC data models– which is always the case in practice as there are many proprietary applications that use their own internal format. One shortcoming of the IFC data model is that it does not allow for the exchange of parametric modelling data which this paper argues, can be very useful for many reasons.

2. The advantages of BIM and data-rich models

Some of the advantages of BIM models shall be highlighted – information rich objects allow multiple disciplines to extract the information they need for analysis. For example, a curtain wall can be used by a light-simulation program – if the material properties were contained within the data. The model could be the same as the one created by the designer and analysed by the structural engineer.

Aish (2000) criticises the current fragmentation of design documentation as the result of the paradigm given by the personal computer where each file is a 'discrete' document stored as a file.

An advantage of interoperability – as opposed to trying to create tools on a single platform, is that the quality of the tools can evolve in their own disciplines. Parametric modelling, in many areas has focussed on geometry – and as a result of the objects being 'immaterial' it requires refinement before it can be used by other disciplines.

This 'metadata' can be an important factor in many practical cases. In design it is rarely the case that some parameter of a model is optimised without some opposing factor being simultaneously considered. For example when increasing the area of glazing or the thermal transmissivity of such an element – there is a cost involved in upgrading the glazing as well as the play-off between heat loss and visual quality – not to say anything about the aesthetic qualities of the façade.

There is a price to pay when it comes to using BIM – and that is the loss of freedom that is associated with geometry-only models, the uncertainty with how to 'classify' elements and the uncertainty by which elements are coupled to properties. It is hard to make general statements that hold true for all cases – but it should be considered that in practice, there are some cases (or patterns) that are more common.

3. What is parametric modelling?

Parametric modelling refers to many different concepts within modelling. The most general characteristic of parametric modelling would be that it produces more than static geometry – a model with a collection of primitive shapes (meshes, curves, points) unrelated to each other. Parametric models contain some form of structure that links elements together or recreates the steps used to create a model.

The most important aspect – for the future development of computational tools – is the embedding domain-specific knowledge into a formal system. This was recognised by Lee et al. (2006) and a lesson should be learnt from the field of computer science where current systems sit above multiple layers of older systems – and how higher level languages are used for greater expression.

There are five concepts associated with parametric modelling that this research is interested in:

A. Explicit History – also known as 'procedural shape generation' or 'History-based models' (Pratt 1998) in other writings. This is the most widely –spread use of the term parametric and software such as McKneel's Grasshopper or Bentley's 'Generative Components' allow for such modelling. These transactions usually take the form of an acyclic graph.

B. Association – which is also known as constraint satisfaction and is covered in the ISO standard for product design. To make advances in parametric modelling, it is essential that some control can be exerted over the sketches and profiles that are used by the model.

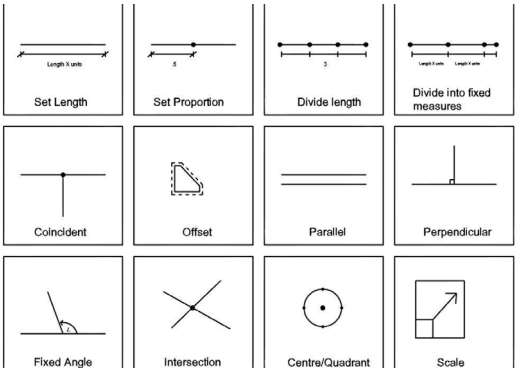

Figure 1. Constraints and modelling features.

C. Types – in programming, the word 'inheritance' is used as a formal mechanism for classes to derive their attributes and operators from a base class. This gives a 'is-a' relationship between objects. For example under the abstract class of 'Person' – two objects that inherit all the properties of

person could be ‘man’ or ‘woman’ – each ‘is-a’ person and can be used in a context where a ‘person’ entity is needed. In the case of modelling software an example is where a beam type can be replaced by any other *particular* beam because they both inherit from the same base class.

D. Patterns and Perspectives – In many industrial design tools, collections of parts are called assemblages. These are allowed their own variables which can modify some qualities of the assemblage. The manipulation of an assemblage might require a special ‘view’ or ‘perspective’ – in detailing the frame of a wall, an elevation is needed – a program manipulating spatial adjacencies might have an interactive graph control. The choice of terms ‘perspective’ was adapted from the work of Haymaker et al. (2004). It is used to describe a certain ‘point of view’ during the design process and can range from an orthographic drawing, a perspectival projection or a symbolic list. While it may seem a trivial point to give a name to something so basic to design, it should be noted that certain constraints related directly to the perspective where it is created. An example of this would be facade composition.

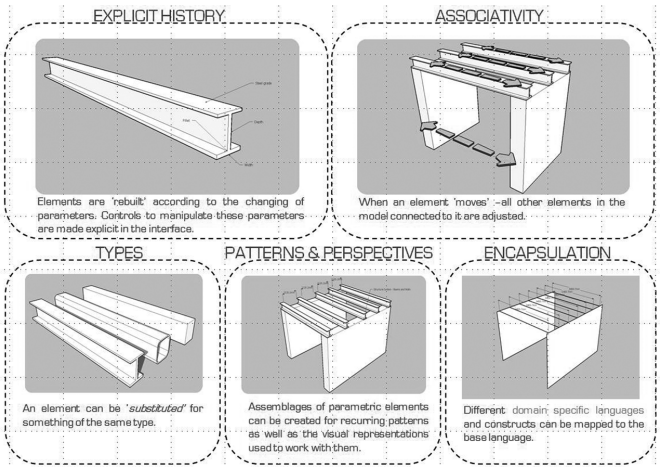

Figure 2. The five aspects of parametric modelling that this research works with.

E. Encapsulation – The features created for BIM work at a very low level – in order to become more expressive, there is the need to deal with more complex configuration using high languages. As an example consider the operations that could occur to a curtain wall – various parameters could be adjusted that change its properties. In a parametric model these operations are contained within the data-object. Encapsulation is essential for ‘intelligent’ objects.

4. Data in a building information model

The diagram below shows the various sets of information that is present in a BIM component. The two sets shown capture a generic list of properties and one definition that is particular to materials

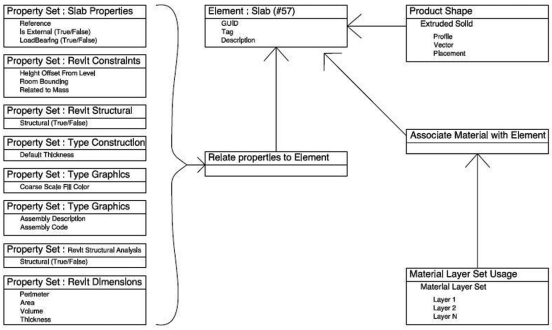

Figure 3. Property data within a model (based on IFC exported from Autodesk's Revit).

Note how the object itself does not contain data – other data objects 'point' to it instead. With a parametric model, the geometry needs to be 'rebuilt.'

As a result, there is a need for re-evaluation of constraints and a 'geometry building' process is needed. Figure 3 shows the three main components of the data carried in a slab – The generic properties, the material properties and the geometry. In this particular case, some of the default properties exported by Autodesk's Revit are shown. If the model were adjusted to capture parametric data, then one possible implementation would be as follows:

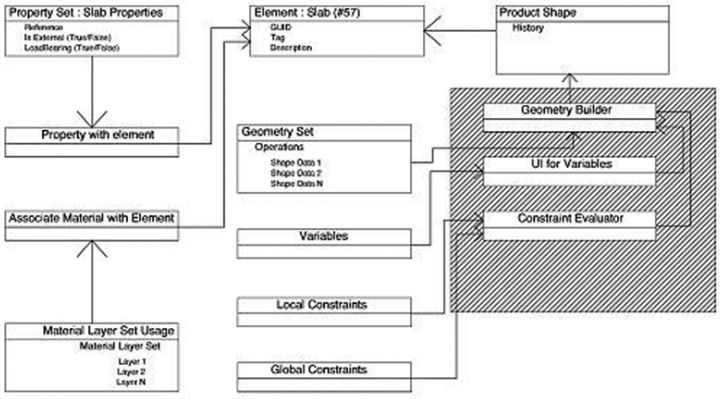

Figure 4. Elements of a parametric object.

5. Generative design methods

'Generative design' is a much looser term than 'parametric' modelling and can encompass any design process where a given 'process' generates some outcome that is then interpreted for its design merit. For illustrative purposes, a famous example 'Reptiles' designed and implemented by John Frazer in 1968 shall be used. This example is illustrative because it set the foundation for later work including the use of evolutionary tools for optimisation – field that is very topical today.

The 'Reptiles' (or REPetitive TILing') described a system of folded plates made from tetrahedral units that encompass enclose a structure. This system had various advantages over the enclosure systems that were known at the time. As the Reptiles article from 1974 described – most of these systems have trouble when dealing with existing orthogonal conditions. The system consists of two types of folded plates one with the vertices of two faces of a tetrahedron and the other similar but with an angle of 90 degrees between the edges. Each of the tiles was described using coordinates in a 3 axis grid:

> *The unit is located in a 60 degree grid with simple whole number 'A' and 'B' coordinates (range -9,99)) ... A 'D' co-ordinate describes depth of the unit. The type and orientation of a unit are described by two digits, the first giving the type and vertical orientation, the second the orientation in the horizontal plane.*
> *This whole description of the unit in space takes the form, for example, -66, 32 24 21, and is packed into one word of core space.*
>
> Reptiles – Frazer (1974)

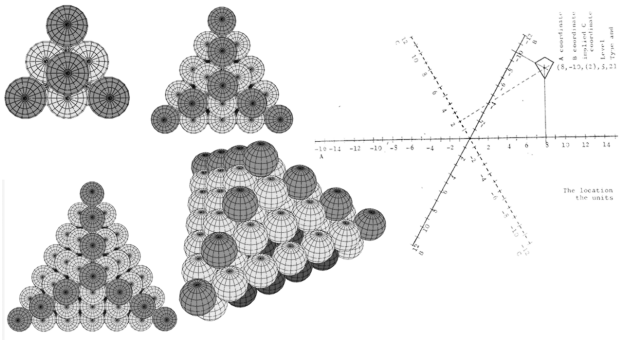

Figure 5. Iterations in the growth process and image from Frazer's Reptiles (1974).

One of the interesting features of the program was that it began growth from a seed – two particular seeds the 'knot' and the 'star' were given and from

them many variations formed. This was a way of keeping the structure from remaining completely closed. In the recreation, we use Lindenmayer systems to recreate this 'growth' process. The L-systems operate on a grid similar to the original one as an intermediate step; spheres are used to represent the cells of the grid.

Each sphere (or cell) is linked to the 12 neighbours that surround it. For the recreation, we then use the following rule-replacements:

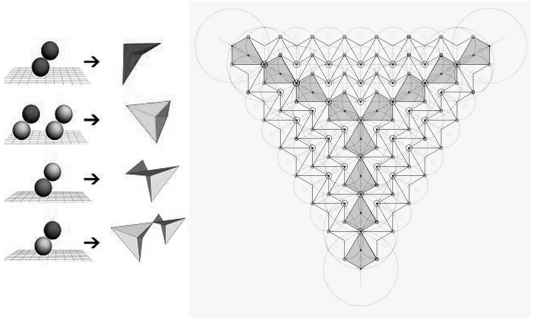

Figure 6. Rules for replacement and the structure after four iterations.

Figure 6 shows the structure after four iterations in the growth pattern. We now consider how this structure could be moved to a larger framework.

6. Using BIM to describe Reptiles

While this example was used for illustrative processes, there are many several lessons that can be gathered from this process. The most important being the coordination of the various units that evaluate code or scripts. The proposed architecture looks as follows:

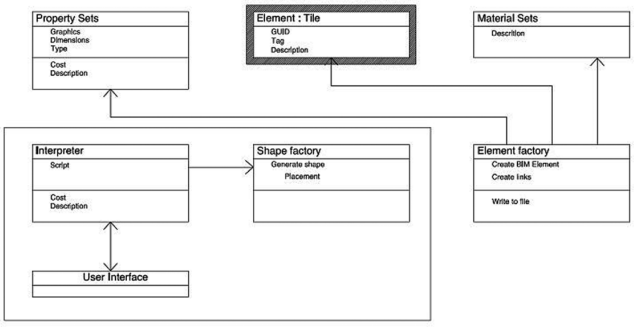

Figure 7. Having a tile produced by the element factory.

We introduce two conceptual units – the 'Element factories' - which help to automate the task of creating the object in the model with all the necessary references and the 'Interpreter' which can read an interpreted language. In this case, the language read is 'C#' The interpreter does not have to strictly follow the single thread of going from an input through a single process to an output, if concurrency is considered in the system architecture.. The following properties and representations shall be assigned to a tile: A cost, an outline which can be used for structural calculations and surface geometry for visualisation. Once an element has been established operations typical of parametric modelling can be performed on it.

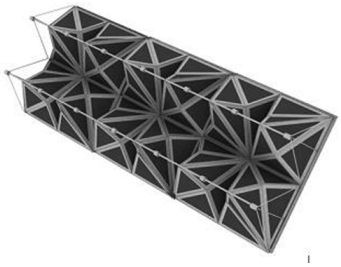

Figure 8. Truss system adapted from the base geometry of the 'Reptiles' tiles.

6. Conclusion

Parametric models require more thought and planning than traditional models. They have two main advantages over static models. The first of these is the ability to make changes to the model rapidly and the second is to collect domain specific knowledge by creating assemblages that can be adapted to a given situation.

The approach to CAD using multiple unrelated files has been criticised by many as not being flexible to changes. It also means that the design process is likely to be a serial process instead of an iterative one. To be truly multi-disciplinary, a building information model is needed, as many of the disciplines outside of design, require meta-data and semantics to assess the model. This is because many disciplines require data beyond the geometry of the model – such as material and cost data. Some approaches such as Life-Cycle cost analysis require locations, so that the amount of energy embodied by the materials and their transportation can be calculated.

There is a currently a gap between the use of parametric and generative tools and modelling in practice. By generative design methods, we include work done with approaches as diverse as cellular automata, genetic algorithms, shape grammars, agent-based modelling etc. These techniques are

often deployed in explorative design. Allowing for parametric and generative methods within industrial standard tools can allow for a greater exploration of design. Including parametric modelling in a BIM framework however, brings with it some challenges as there is a need for more modules to handle the constraints, geometry building and input from the users. With generative design methods there is also a need for an interpreter to read the scripts that are used. In this paper, the 'Reptiles' project from 1968 was examined as it set the foundation for many generative experiments in architectural design. The aim was to utilise a cellular automata-like representation to fix local errors and create ensure only 'valid' models are created. Adjustments were made to how it might incorporate object data into its representation.

With regard to the second advantage mentioned of parametric modelling – the capturing of domain knowledge, it is an essential step that human designers work with higher, more expressive tools over time. One way in which this is possible, is by translating concepts form object-oriented modelling such as inheritance and encapsulation. By allowing this, a bridge can be made between the conceptual and developed stages of the design process, it also means that performance analysis can be conducted sooner and be part of the initial design explorations. As yet, there is much to be standardised with regard to parametric modelling in BIM.

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BENDING CURVATURE

A design tool for interactive complexity

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Abstract. Bending is a phenomenon that occurs with great frequency due to the presence of natural forces like gravity, wind. It occurs whenever an element is subjected to an external load applied perpendicularly to its longitudinal axis. Every known element, independently of its stiffness, exhibits certain amount of bending. This paper explores this phenomenon not as a failure mode to provide tolerance for, but as a tool to design with. The design research presented here emerged from a combination of digital explorations calibrated through analogue experiments of bending rods. The aim was to create a model that would incorporate the interaction between bending rods and the transfer of forces. Rods were connected to each other with rings that allowed for certain degree of freedom, though limiting them to be in contact with each other at all time. The rods started bending in various planes; their curvature is negotiated with that of their neighbours and thus a process of self-organisation with multiple parameters was present until equilibrium was attained. Intrigued by this observation, this research seeks to look at bending as a possible design tool. Understanding the behaviour of a single element in its simplex situation and simulating this behaviour in a computational environment has been the starting point for building up a model where complexity is built progressively as a result of local interactions among several bending rods.

Keywords. Bending; geometry; simulation; parametric design; optimisation.

1. Introduction

The research presented here explores bending as a design tool. It was initiated as part of a postgraduate academic agenda by the authors and has been

further developed ever since, including numerous experiments using a range of analogue and digital form-finding methods. This research looks into the aesthetical and structural aspects of a system that employs elastic bending as a method of prestress, creating structurally efficient assemblies for a variety of uses in lightweight architecture.

Though bending for architectural applications has been used since ancient times for the construction of huts and bridges (Dunkelberg 1985), the actual geometry of bending has not been studied in depth until very recently. The digital representation of a bending rod can be modeled using several different approaches approximating its form to a great extent. Architect Marten Nettelbladt has been experimenting with the geometry of bending and has created an important online resource of experiments and observations concluding that all 'elastic deformation' follow the same principals and therefore the same geometry (Nettelbladt 2008). A more recent development is the "Kangaroo" physics engine for interactive simulation, optimisation and form-finding within Grasshopper plug-in in Rhinoceros, developed by Daniel Piker; this can provide excellent results for the simulation of a single bending rod. This engine works in an iterative way calculating the interaction among predefined forces like springs, bending resistance, pressure and gravity, and their repercussion on the geometry, until a stable form is reached. As our research looks at bending as a design tool, the experiments conducted involved several interacting rods adding to the complexity of the system. The physical form-finding experiments revealed some unpredictable results that emerged from the self-organisational capacity of the system to regulate and distribute forces to reach equilibrium.

2. Form-finding experiments

The principles of construction utilised in our experiments have been extensively used in Bamboo structures. Frei Otto refers to them with the generic term *"Curved Compression Rods"* referring to arches, grid shells and other structures *"whose form is determined by installing curved – and thus prestressed rods"* (Dunkelberg 1985).

As part of this research two sets of analogue experiments were conducted. The first set employed material with thickness smaller than 1 mm, such as piano wires (Figure 1), focusing mainly on morphological and geometrical aspects, and the second set was conducted with GRP (Glass Reinforced Polymer) rods (Figure 2) that could also give an insight into structural issues, joints and forces; both sets aiming at understanding the behaviour of bending and the interaction among rods. Glass Reinforced Fibre is an anisotropic material with high Young modulus. When casted in form of a rod, the fibres are aligned along the length giving the material high elastic strength with flex-

ibility to bend. It also attains a high elastic limit thus allowing us to conduct experiments in cases that piano wires would get a permanent deformation.

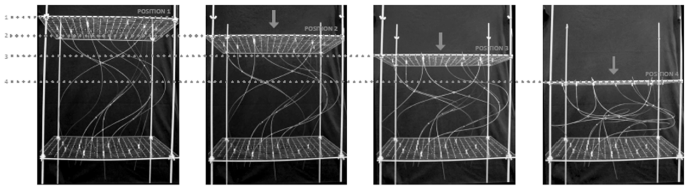

Figure 1. Form-finding experiments with interacting piano wires exploring bending and buckling in 4 different positions along the z axis.

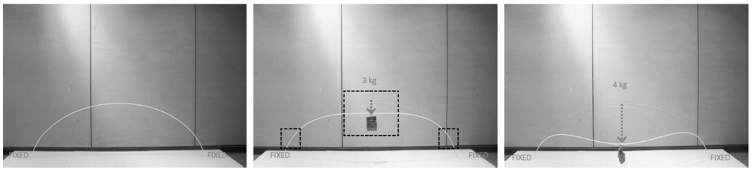

Figure 2. Loading tests with 9 mm GRP (glass reinforced polymer) rods with two fixed. connections.

3. Observations on physical experiments

The above mentioned experiments aided us to formulate questions that would further push the research forward. Looking at a multiple rod system, it is really complex to understand the interaction between the curves, the geometrical aspect and factor that governs the extent of deviation. Through experiments with piano wires, we looked at aspects like torsional buckling and twist. One of the intentions was also to understand which are the stable positions of curves in terms of energy, though this was out of the realm of geometry and was not our primary aim. In the second set of experiments, curvatures were understood as being the governing factor for dynamics shown by the system. This was further tested by means of simple loading experiments. After a certain loading limit, the curve left its 2D plane in quest for a more stable position under those conditions (Figure 2).

In a system with multiple elements, the joints are actually points where the force is exerted. The amount of force depends on the value of curvature and the deviation is based upon the location of points with respect to the change of curvature. Therefore, by means of experiments this behaviour was tested and understood. Throughout the experiments, which started with single element, joints, and multiple elements and finally developing assemblies (Figure 3), curvature was observed and looked upon as a factor of interaction. It must be noted

that for experiments, force was applied to create displacement and its quantum is not relevant. Through a series of experiments, the behaviour of bending rods was catalogued in detail with the aim to understand and extract the parameters that control the geometry of interacting bending rods (Figure 4).

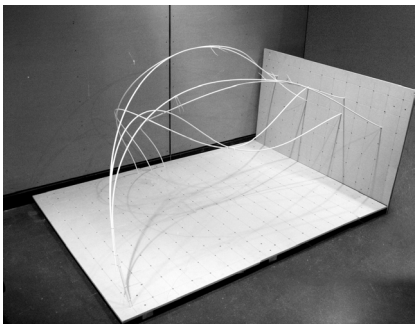

Figure 3. Model with multiple GRP (glass reinforced polymer) rods with fixed connections.

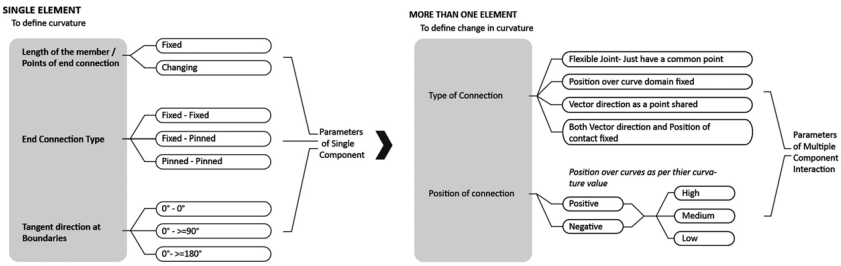

Figure 4. Diagram of parameters for GRP rod experiments.

4. Digital tools – A computational approach

Following the analogue form-finding experiments, a set of computational explorations aimed to further highlight the principles that affect the geometry of bending and the complex behaviour that arises from the interaction among bending rods. The physics algorithm employed here is partially based on a spring system with global and local parameters controlling each of the elements that are represented by lines and points. An environment is also defined to simulate the geometry. The algorithm is based on Stylianos Dritsas Physics engine published online in 2008.

The tool works on a geometrical model consisting of lines and points predefined by the user to achieve a particular behaviour. An inherited position

continuity is maintained and due to the connectivity, the resultant vector is also tangent continuously. Variable flexibility controlling the curvature capacity, length constrains, degree of freedom at ends and at junction, can be defined using local parameters and can be recalibrated after running the simulation to fine tune the form. By implementing certain pieces of code, analysis can be embedded during or after the simulation, thus offering opportunities such as mapping of trajectories, stress mapping, minimum volume enclosed among others and even generate a feedback loop system.

5. Experimental understanding of bending

The geometrical effect of bending has been studied through physical and digital experiments. Although these two approaches have been carried out separately, they have been informing each other in various phases.

The first stage was a set of physical experiments that provided us with a detailed catalogue documenting the behaviour of the rods, alone, in small assemblies and under the influence of external forces. The digital approach is not a copy or a recreation of the same experiments in digital environment, it is an abstraction of the self-organisational principles of the rods and an attempt to simulate that behaviour with digital means. There are numerous factors that define the configurations obtained by the rods. Apart from the characteristics of the material (stiffness, rod diameter) the obtained geometry depends on their boundary conditions (position, degrees of freedom, tangency), the length of rods, the type of nodes among rods, the forces acting on the system (global, local). The manipulation of these parameters gave a number of different spatial configurations. The type of nodes selected and the geometrical configuration (curvature, direction and tangency of the rods) can enhance or constraint the load bearing capacity of the system. In the case of interacting rods, the configurations obtained are not a direct result that can be predicted before the experiment, they are rather an emergent result of the local interactions of forces acting on the rods.

The digital experiments employed springs simulating bending behaviour; various cases were studied, joining the springs alternately for continuity in the material, using truss logic to counteract torsion twists, experiments proved that the combination of springs acting under tension and compression proved to be the most efficient in simulating the rod behaviour.

Generally, physical experiments have explored the macro-behaviour of rods, while the digital experiments have focused on the micro-behaviour within one rod. These investigations aim at creating a design tool for interactive complexity; the understanding of the material constraints and the interaction of forces inform the design process of an architectural object or artefact.

6. Pedestrian bridge – a case study

The above research was further developed through a case study, utilising the findings and integrating them with additional architectural parameters for the design of Pedestrian Inhabitable Bridges - A Multi Responsive Form Finding Exploration (Figure 5), a design thesis written by architect Utssav Gupta as part of a post-professional degree in architectural research and design, at the Architectural Association in London. This project serves as a case study to test, analyse and develop an experimental algorithm that looks at bending as design tool through the use of simulations that constantly update a geometrically complex model through feedback loops.

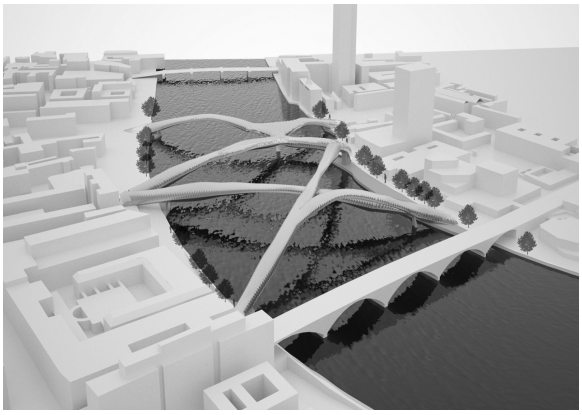

Figure 5. Pedestrian Inhabitable Bridges over the river Thames by Utssav Gupta.

6.1. A TOOL FOR MULTI-PERFORMATIVE STRUCTURES

Bridges are transitional spaces and their design usually involves a large number of parameters. From a structural point of view stability and damping are key issues. Architectural and urban criteria on the other hand, require contextual integration. In this case, with London city acting as the site for intervention, the architect's vision was a subtle design that would not disturb London's sky line, a smooth flowing corridor connection between the areas around King's college and South bank, over the river Thames. Since the river is navigable, there have been certain parameters ranging from port authority to river bed contouring that formed part of a set of design constrains. A multi branching system was deployed having different programs for each span responding to culture and context on each side. For a span with variable sections, each with different contextual conditions and responses, the algorithm finds a topology

that locally responds to constrains and yet maintains a global continuity and flow. It embeds structural principles to generate a viable solution.

Since the tangential continuity was a major concern in the topology, principles of continuity achieved in a bent structure were adopted, hence utilising the tools described in the first part of this paper. Through simulations and further development of the code, the aim was to create solutions for topology and path finding, form-finding and optimisation. For a multi-branching system with no particular convergence points and with different architectural program, each of the sections were unique and were required to be aligned keeping in mind the local curvatures, rise, loads, views, context, along with the overall calibration and smooth flow of branches in and out of each other.

Most of the key issues and their translations were found to be affecting each other, either by aiding or opposing certain parameters, for example, navigability required height clearance and a higher apex for structural stability, however from a pedestrian and urban point of view, a steep corridor was undesirable. Branching itself held a huge potential for achieving structural stability against self-load and wind load as well as in streamlining the path. Collating all these variables and embedding them into the previously discussed tool lead the simulation behaviour towards that of an optimisation code. Though many multi-variable optimisation theories have been debated upon, Thomas Weise's paper on *Global Optimization Algorithms: Theory and Applications,* has more extensively outlined the nature of most existing phenomena. He has explained multi-variable optimisation simulations as a set of many local minima and maxima beyond which lies a global solution. The developed algorithm displayed a similar behaviour, it unfolds several times to jump over local peak until it attains a final range. It produced a family of solutions which when tested upon Finite Element Model, gave results that were further optimised. A comparison of the outputs shows minor differences in the stress levels, highlighting the optimal solution in a model that had slightly different branch lengths.

Once topological, path finding and trajectory were embedded, parameters for spatial definition vis-a-vis structure were also looked at. In some of the branches, depth plane varied from that of main span and got deeper with a simultaneous increase in stress levels. Cross sections were taken in later iterations of simulations that got optimised further with structure and path flow. In a post-process exercise using a separate code, morphology and surface geometry was developed over the base skeletal grid formation (Figure 6).

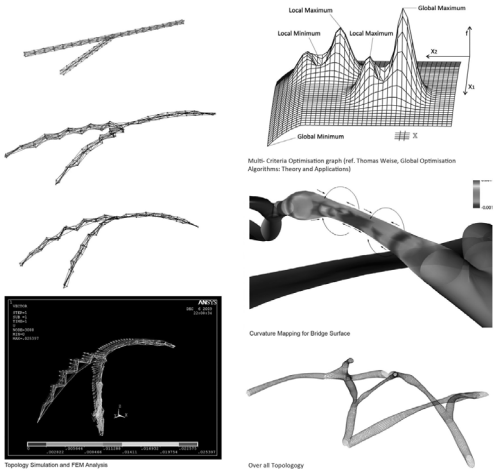

Figure 6. Analysis and design stages of Pedestrian Inhabitable Bridges by Utssav Gupta.

As a base algorithm, the code possesses a hug potential to host a plug in that would perform various tasks and provide data to the main process. Some analytical tools have already been discussed above, but with further form generation aids, it would be possible to develop morphologies adapting to various environmental conditions. Prospects of such a powerful tool are open and its applications could also be versatile.

7. Conclusions and future research

This paper reports on an ongoing research, presenting for the first time some initial results and setting the frame for future development. Throughout this research physical experiments have always informed digital explorations to ensure the quality of the simulations. An interactive design tool is currently under development by the authors, aiming at producing novel design solutions that will utilise the stored energy in elastic bending to give rise to lightweight structures that are both elegant and structurally efficient, taking into consideration material characteristics and force-flow already during the initial design stages. The case study achieved to highlight the advantages and limitations of this new tool for a design task of complex programmatic requirements. The algorithm's great potential lies in the fact that it can cater for multiple parameters at the same time. In this case, the bridge project apart from the structural issues also needed to respond to rise over the river for navigability, path alignment, curvatures for slenderness, and branching; each of which are interconnected and affect each other.

Acknowledgements

The research on Bending Rods was initiated by the authors as part of Core Studio work for the postgraduate course Emergent Technologies and Design at the Architectural Association in London. The design thesis Pedestrian Inhabitable Bridges was presented by Utssav Gupta as part of his March degree. The authors acknowledge the valuable contributions of Michael Weinstock, Michael Hensel, Achim Menges and Stylianos Dritsas during the development of their research.

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PARAMETRIC URBAN DESIGN EXPLORATION IN A GRADUATE DESIGN STUDIO

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Abstract. A city is a typical complex system that composed of billions of individual factors that interact with each other, and evolve dynamically. Parametric design method considers design conditions as the parameters of form generation, and introduces bottom-up emergent process in computers into architectural design. Because of such mechanism, it is supposed that parametric design can be applied in urban design problems, and brings rationality and creativity into urban design. In the year 2011, a joint design studio of Princeton University, Tokyo University and Tsinghua University is carried out. Graduate students from the three universities dive into the design of a micro-city that expands from Haneda airport in Tokyo bay area. The design studio in Tsinghua lasts for 16 weeks, and the students are asked to develop their ideas in a parametric way, and explore the potential of bottom-up generation of urban design using computer tools.

Keywords. Parametric urban design; Haneda airport; complex system; urban form generation.

1. Urban space as a complex system

Modern city is a combination of natural system and artificial system, and is a gray system in which the information is partially clear and partially unknown. An urban system is composed of biological system, infrastructural system, economical system, social system, etc., and each subsystem is composed of smaller subsystems, even basic elements. Some statistical results show that the amount of elements in a city accounts for the amount of at least 10^8. A city is a system with complex structure and diverse functions, it is located in a macro complex environment, and evolves dynamically in the continuous process of exchanges of materials, energy and information (Pei 1999). It could be

said that a city is a complex system which composed of numerous individual elements that interact with each other. The local interactivities finally result in a dynamic development of the whole system (Wu and Li 2010). During the evolving of a city, this kind of bottom-up self-organisational process is combined with the top-down urban planning process, and these two processes decides together the urban form and its development.

Parametric architectural design method is based on the contemporary development of computer technologies, and is greatly influenced by the theory of complex system and non-linear science (Xu 2009), this makes parametric design a method adaptive and of great potential in dealing with planning and design problems of the urban system.

Schumacher (2008) proposed the concept of parametric urbanism, and applied it in his research and teaching. The assumption is that the urban massing describes a swarm-formation of many buildings. These buildings form a continuously changing field, whereby lawful continuities cohere this manifold of buildings. Parametric urbanism implies that the systematic modulation of the buildings' morphologies produces powerful urban effects and facilitates field orientation. Schumacher point out that modernism was founded on the concept of space. Parametricism differentiates fields. Within fields only the global and regional field qualities matter: biases, drifts, gradients, and perhaps even conspicuous singularities like radiating centres. Deformation does no longer spell the breakdown of order but the lawful inscription of information. Orientation in a complex, lawfully differentiated field affords navigation along vectors of transformation.

Leach (2009) considers that city is composed of a large number of smaller discrete elements, and displays a bottom-up collective intelligence that is more sophisticated than the behaviour of its parts. In short, the city operates through a form of 'swarm intelligence'. He points out that the term itself does not necessarily refer to contemporary design issues. On the contrary, it could be argued that emergence could be viewed most clearly in traditional urban formations. Leach points out that the term 'swarm urbanism' has been used fairly extensively within design circles, and he explains the concept of swarm urbanism though introduction of the bottom-up multi-agent generative design of Kokkugia. In this paper, graduate students' works in an urban design studio in Tsinghua University, which is part of an international joint design studio, is introduced. In this studio the concept of complex system is introduced to the students. And the students are encouraged to explore possibilities of bottom-up generative urban design method using computer tools. Three of the student works are selected here which show a variety of exploration of possible bottom-up urban design strategies.

2. The Haneda Micro-City urban design

In the spring of 2011, a joint design studio of Princeton University, Tokyo University and Tsinghua University is carried out. The theme of the studio, proposed by Princeton, is Haneda micro-city design, which intends to study the urban space form related to modern international terminals in the context of Tokyo bay area. Since the design objective is more an open research topic, studios of different universities are able to explore design strategies according to their own understanding and interests.

In the past 30 years, Narita Airport has been considered the central hub connecting East Asia. But Narita is far away from Tokyo, an obsolete facility that is expected to be replaced by a new hub. In response to these pressures a new international terminal was completed at Haneda which, benefits from its proximity to the metropolitan centre and access to high-speed rail. The federal and local governments however, recognise that the new terminal is only a partial solution to the problem. They are striving to create an attractor for international travellers as a way of re-centring Japan in the new Asia. Metropolitan planning initiatives have recognised the importance of developing a new urban centre in proximity to Haneda. The intension of the design studio is to discuss the possibility of such urban centre.

During the early stage of the studio, the students are required to study the ideal urban design theories, such as Garden City, Archigram, etc., also including the Tokyo bay project of Kenzo Tange. Tange's urban planning project in Tokyo bay has a far-reaching influence on the development of this area, including multiple aspects related to urban planning. This kind of study becomes one of the important start points of the students' designs.

On the other hand, the students are encouraged to explore possible bottom up generative design strategies using parametric design tools. It is expected that computer could be employed in the simulation of self-organisational development of basic urban elements, which can result in urban design that is adaptive to the functional requirement and the law of development of urban space. As mentioned above, parametric design method has great potential in dealing with large amount of urban elements that interacts with each other. In this design studio, it is also expect to explore possibilities of parametric design methods for urban design in this kind of research through design (Herr et al. 2011).

3. Student works

The design studio in Tsinghua lasts for 16 weeks, and 10 graduate students are divided into 5 groups. Parametric methods and computer tools are used extensively in most groups, and at the end, the design results display new

exploratory organisation and possible urban structure of future cities. Some of the students' works are introduced below.

3.1. FLOATING AGGREGATION – JELLYFISH CITY

A lot of historical cities grow up in a bottom-up way without planning, but finally resulted in a good city form. The design here uses the method of diffuse limited aggregation (DLA) to simulate such an evolutionary process in which a small village grows into a huge urban complexity. DLA is the process whereby particles undergoing a random walk due to Brownian motion cluster together to form aggregates of such particles ("Diffusion-limited aggregation" 2011). It is supposed that a village in the sea can be initiated by random aggregation of small boat houses. When the village expends, and as the density of its centre area gets higher, permanent multi-floor buildings emerge (Figure 1). In the final design, an aggregation of high rise buildings was located in the centre area of the city, and a branching road system extends to the periphery area, where floating boat houses dock and become part of the city (Figure 2).

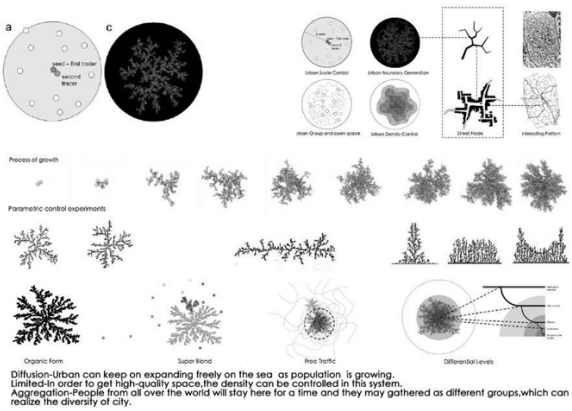

Figure 1. The city form generation using DLA.

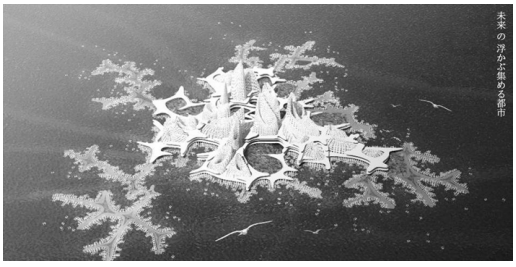

Figure 2. Bird view of Jellyfish City design.

Since this kind of aggregation mechanism is developed based on understanding of bottom-up growth of historical cities, the result turns out to be organic and dynamic. On the other hand, the DLA has generated a road network which is too complex, and not so efficient for a modern city. Future research may discuss how to develop DLA into a method that can generate better form of a modern city.

On the other hand, through study of jellyfish, a self-sufficient living model is found. By reaching out its tentacles, jellyfish obtains energy from the sea that support its metabolism. The city is also considered as a living organism that obtains energy such as tidal energy, temperature-difference energy, salinity gradient energy, wind energy, etc., from its environment. Hair system in Autodesk Maya is used to generate a road and utility tunnel system that reaches out into the sea (Figure 3).

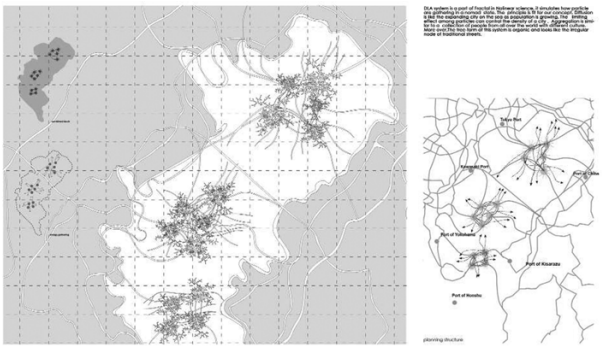

Figure 3. The road and utility tunnel system generated by hair system of Maya.

3.2. FUJI MOUNTAIN IN THE SEA

The discussion of ideal city could not only refer to the future. One can also go to the history, and get idea from traditional images.

Through study of the painting Fugaku Sanjūroku-kei by Katsushika Hokusai, it is found that the scenery of Fuji mountain is of great importance for the area of Tokyo bay. Because of this, the form of fuji mountain is selected as the prototype, and a scattered distribution of this prototype is used in the urban design, in order to rethink the contemporary land reclamation activities.

Computer simulation is used to generate an optimised scattered distribution of units. Three basic megastructure units of different scale are considered: scale of living block (diameter 200 m), scale of a business zone (diameter 400 m), and scale of urban complex (diameter 800 m). Possible distribution of these three types of units with hierarchical relationships are generated using com-

puter programs, and the ones adapt to sailing route are selected (Figure 4). On the other hand, illuminated by the wool thread experiment of Frei Otto, a rhino script program is written to simulate the evolving process of deformation of wool thread, and generate organic road network for the design (Figure 5).

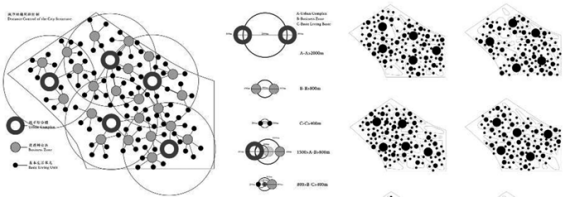

Figure 4. Generation of distribution of 3 types of megastructure units.

In order to introduce natural light and open space to the megastructures, a minimum surface system is used to split each megastructure into functional space and void space (Figure 6), which gives the megastructure a more complex and organic form that contains multiple functions.

In this design, the parametric design methods can be used not only to organise urban functional spaces in an emergent way, but also used to generate beauty with regularities, such as the water wave like forms in this design. This kind of design concept is not a generated in a bottom-up way, but rather constructed in the student's mind. This project demonstrates that the aesthetics of a parametric design can be decided by a the architects based on their understanding of generation and aggregation logics of algorithm.

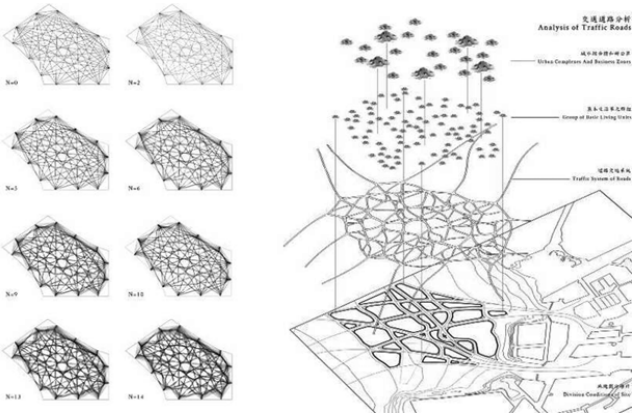

Figure 5. The road network generation (left) and layers of the urban design (right).

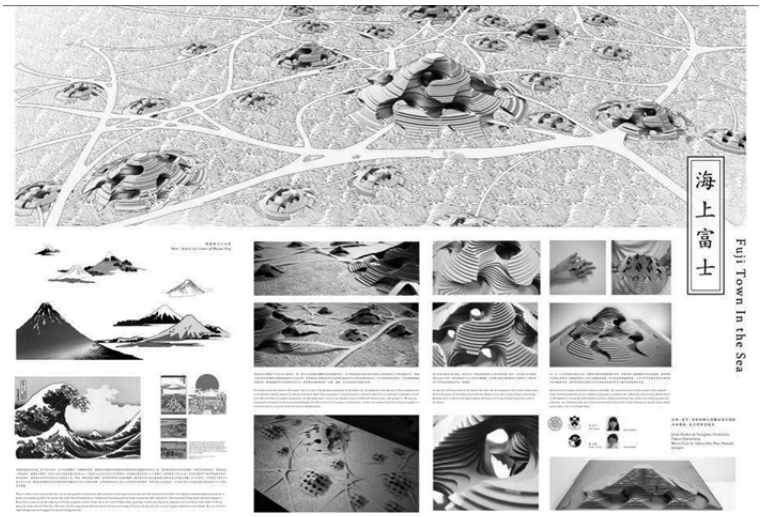

Figure 6. The final design of Fuji Mountain in the Sea.

3.3. BRIDGE CITY

In order to solve the problem of severe damage on environment and ecosystem caused by land reclamation, and deal with the confliction of city and nature, a new model of city and nature is designed, which is, to hang the city above nature. The idea of the design is to build towers with the height of hundreds of meters, which hold up gigantic cable network in the sky, and hang buildings beneath it to form urban clusters above nature (Figure 7).

An urban development axis is selected which is the same as the Kenzo Tange Tokyo bay project, and the city grows along the axis from west to east. A Voronoi grid is used to generate the urban blocks. The grid is denser in the middle area and more spacious on the sides because the vertical density in the city centre is higher, which is heavier for the cable network, and heavier in traffic, so the grid is made denser to deal with this problem (Figure 8).

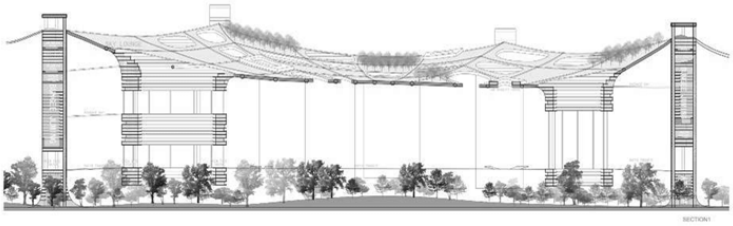

Figure 7. Section of a block of the Bridge City.

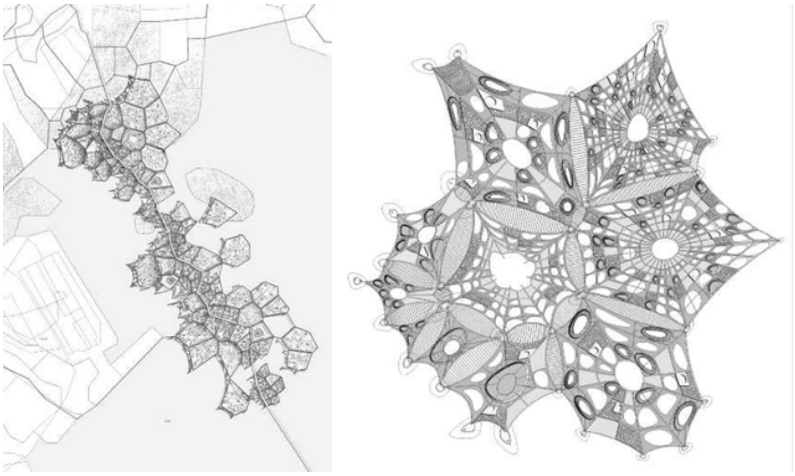

Figure 8. Site plan (left) and plan of blocks (right) of the Bridge City.

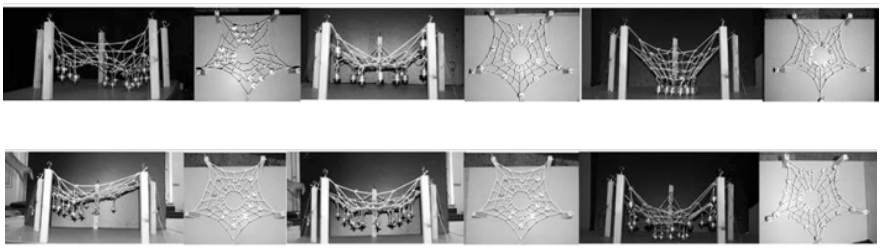

Figure 9. Physical experiment for form finding considering gravity.

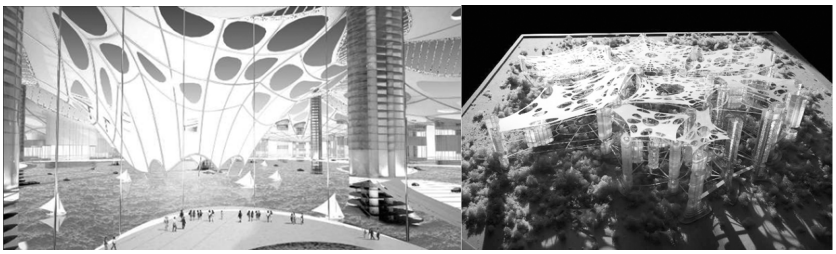

Figure 10. Model (above) and perspective of the natural sea level (below).

In the final design, forest and sea level are preserved as the original state. On the top of the bridge city, a green public space is formed. The great holes allow sun light to get to the city, and the nature beneath it.

Since the function distribution in each block is different, which gives different load distributions to the above cable networks, physical structural experiment of cable network is carried out as a way of form finding for urban blocks based on gravity (Figure 9). A traffic system is placed at the bottom of the hanging buildings, which provides tension forces, and makes the whole system stable (Figure 11).

4. Conclusion

The exploration of application of parametric design method in urban design is still at its early age. In the three postgraduate students' works shown in this paper, different computational or physical methods are used to organise urban elements in a bottom-up way. Since the students have constructed their logic based on rational understanding of urban design problems, urban forms generated through these self-organisational methods are more organic, dynamic, and more rational in certain aspects. At the same time, although the tutors emphasised only bottom-up design strategies in this studio, the students all choose certain top-down strategy to control the general form. This may because that the graduate students have a better mastery of design techniques, and would employ such techniques in the design process in a very natural way. The top-down strategy plays an important role in controlling and selecting the bottom-up generation results, and in the development of the aesthetic performance of the design. In the end, the top-down and bottom-up design strategies become complementary in the designs.

It is expected in the studio the self-organisational generation in computer could lead to good city forms that are similar to the historical cities with very attractive urban spaces. But it is hard to say that the designs of this studio are efficient according to the requirement of a modern city. Further researches may explore the possibility of solving both the problem of space quality and efficiency at the same time by the method of self-organisational generation.

Notes

1. The tutors of the joint studio are: Jessie Raiser and Nile Cook from Princeton University, Kengo Kuma and Yusuke Obuchi form Tokyo University, and Weguo Xu and Weixin Huang from Tsinghua University.
2. This research is supported by the National Natural Science Foundation of China (No. 51078218)

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VISUAL TRAINING IN VIRTUAL WORLD

A comparative study between traditional learning versus learning in a virtual world

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Abstract. This paper presents a comparative study of Architecture students who study in a tradition learning environment and Innovative Design students who study in a 3D virtual environment. Both groups share the same objectives. Their learning pattern went through a three-step learning process where issues related to Design Composition theory were inserted. A survey and an in-depth interview showed a discontinued creative process amongst Architecture students due to class management. It showed that Innovative Design students should have more small assignments to better understand issues related to Design Composition theory with emphasis on developing their communication skill in using Visual Training technical terms. The differences between the two learning approaches were discussed.

Keywords. Visual training; OpenSim; design learning; virtual world.

1. Introduction to visual training at Rangsit University

Visual Training is a class where students learn about visual elements in order to develop skills and understanding of the artistic composition theory, starting in the arrangement of two dimensional elements and developing into more complex three dimensional designs. In a traditional Visual Training class, students use conventional tools like drawings, paintings, and 3D models (both physical and computerised) in their design.

Last year (October 2010 – January 2011), we introduced a Virtual World to a small group of students by using OpenSim (Nakapan and Gu 2011). OpenSim showed potential to serve as an alternative platform for design and

collaboration. It responded satisfactorily to most of the issues investigated in the Visual Training class, especially basic visual elements (dot, line, plane, colour, and texture) and issues related to the relationship between humans and environment (human scale, 2D, 3D elements). However, the available papers did not thoroughly investigate how the platform responds to more in-depth issues in design composition theory where the meaning is involved, such as identification of character, sensory, mood and sequence.

This paper aims to investigate these issues of Visual Training. Its objective is to show how learning in a virtual world can respond to issues related to Visual Training, in comparison to traditional learning. The paper also aims to show the limits of a Virtual World learning environment and how assignments have to be adjusted in order to meet the objectives of the class.

Many similar works are found in the field of Virtual World learning. Some focus on the communicative aspect, such as Clark and Maher (2005) that studies the role of place in a virtual learning environment for digital media design in the context of Virtual Design Studio. Abdellatif and Calderon's study (2007) describes a demonstrative experiment where students had to communicate with their tutor and display and describe their projects at a distance, in a purposely designed criticism space in Second Life. Some are more interested in the collaborative aspect of the virtual world. For example, Hoog et al. (2007) from TU-Vienna provides a 3D virtual campus as an extension to the existing Moodle and has tested three virtual environments as collaborative labs (Open Croquet, Blender and Second Life), for teaching architecture, and as digital environmental design tools. Merrick and Gu (2011) analyses virtual worlds with reference to the technological facets that can support collective intelligence in design, presenting the case of *Lego Universe*.

2. Learning process in two parallel classes

The class begins in July 2011 with two groups of students. One is a large group of 300 students in the Architectural Program who learn in a traditional Visual Training class. A smaller group consists of 20 students from the Innovative Design Program who do their assignments in Virtual World (OpenSim). These two groups share the same course syllabus and core lectures during the first two years. The assignments vary according their learning environment and the given assignment.

2.1. THREE STEPS LEARNING PROCESS

The learning process consists of three steps, one for each learning objective. The first step is "research and analysis" where students learn to search for

information that supports their idea. The second step is "logical and divergent thinking" where the students learn to find alternative solutions to a given design problem. The third step is "logical and creative thinking" where students create a small architectural piece integrating all the design issues they have learned. Communication is part of every step of the learning process and students are required to communicate their thinking and design via various group presentations and discussions.

2.2. ISSUES RELATED TO DESIGN COMPOSITION THEORY

These in-depth issues related to design composition theory are inserted into the three-steps learning process in the Visual Training class:

1. Identification of character,
2. Transformation of context,
3. Visual Elements (after Identification of Character + Transformation of Context),
4. Design Composition,
5. Mood,
6. Sensory,
7. Human scale,
8. Sequence.

While Identification of Character corresponds to "research and analysis" and Transformation of Context corresponds to "logical and divergent thinking", the majority of the issues (no. 3–8) are introduced in the last step of "logical and creative thinking" at which point architectural-related issues are introduced.

2.3. TWO DIFFERENT APPROACHES

For the two groups to meet the same objective of the class we took different approaches in the problem given to Architecture students and Innovative Design students. A bottom-up approach is used with Architecture students who have to identify the character of an animal of their choice and transform this into 2D and 3D models. Due to the limitations of the Virtual World platform, a top-down approach is used with Innovative Design students who have to imagine an "Avatar World", a biosphere based on their research of real-world information (the planet, fauna, flora, intelligent species, …).

Once the animals and the "Avatar Worlds" are identified, both approaches have to undergo a transformation of context. The objective is to identify the result from a change of environment and to find a solution for survival (redesign). The situation given to Architecture student is to identify the mutation of animals resulting from a rise of global temperature. Innovative design stu-

dents have to identify the adaptation of the imagined "Avatar World" in order to create it on a 256 × 256 sq-m island in OpenSim.

Architectural Design is introduced towards the end of the class. Architecture students have to design a pavilion based on the identified animal character, while Innovative Design students have to build a pavilion to exhibit of their "Avatar World". At this point of time lectures about visual elements and design composition theories (sequence, sensory, mood, …) are given.

3. Students' learning outcome

The following pictures show the learning outcome of the students, resulting from the three-step learning process. Figure 1 shows the learning outcome of Architecture students (upper row: an analysis of the cheetah's life, middle row: an analysis of the cheetah's mutation due to rise of temperature on Earth, and lower row: a final model of a pavilion inspired by the cheetah).

Figure 1. Learning outcomes of Architecture students.

Figure 2 shows the learning outcome of Innovative Design students (upper row: a conceptual video, middle row: a Machinima (story telling video) showing a transformation of context from imagination to OpenSim, and lower row: a final video of an exhibition of the avatar world).

Figure 2. Learning outcomes of Innovative Design students.

4. Questionnaire

A questionnaire is used to compare the learning outcome of the two groups e.g. how well students understand or apply each design issue introduced in the

class. Using Likert scale (Likert 1932) the interpretation of the results follows this guide based on an interval scale of the average score: 1–1.8 very badly, 1.81–2.6 badly, 2.61–3.4 neutral, 3.41–4.2 well, 4.21–5.0 very well. Table 1 shows the 8 questions that are asked in the questionnaire according to each design issue, with one additional open-ended question.

TABLE 1. Questions asked in the questionnaire.

Design Issues	Architecture students (Bottom-up approach)	Innovative Design students (Top-down approach)
1. Identification of Character	After you have studied about an animal of your choice, how well can you identify its character?	When you have studied about existing things in real world, how well can you create an imaginary world to be of a unique character?
2. Transformation of Context	How well can you analyse the mutation of an animal for its survival due to a rise of temperature?	How well can you transfer your imaginary world onto the 3D virtual world (OpenSim)?
3. Visual Element (+ Identification of Character + Transformation of Context)	How well can you interpret an animal's character and its mutation due to the transformation of context into visual elements?	For the creation of your avatar world on OpenSim, how well can you convey the identity of your avatar world into visual elements?
4. Composition	After you have studied about design composition theory, how well can you use it to improve your design?	After you have studied about design composition theory, how well can you use it to improve your design?
5. Mood	How well can you use the character of an animal to create mood in your design?	How well can you use the character of your avatar world to create mood in your design?
6. Sensory	How well can you use the character of an animal to create sensory in your design?	How well can you use the character of an animal to create sensory in your design?
7. Human Scale	How well can you create spaces that correspond to human scale?	How well can you create spaces that correspond to human scale?
8. Sequence	How well can you create sequence that result in the perception of mood?	How well can you create sequence that result in the perception of mood?
9. Open-ended question	How will you use the knowledge from Visual Training class in architectural design?	How will you use the knowledge from Visual Training class in architectural design?

Table 2 shows that students perceive they can understand the identification of character well (3.74 for Architecture students: 4.11 for Innovative Design students), can redesign due to the Transformation of context well (3.58:3.78, can

create mood well (3.63:3.89), can create sensory experience well (3.47:3.89) and can create sequence for the mood well (3.45:4.11).

However, Architecture students indicate they can use visual elements to interpret the mood well (3.66), while Innovative Design students indicate they can do it very well (4.22). Architecture students indicate they can use design composition well in their design (3.95), while Innovative Design students indicate they can do it very well (4.44). Finally, Architecture students indicate they can create space according to human scale well (3.68), while Innovative Design students indicate they can do it very well (4.22).

TABLE 2. Questionnaire results.

	Steps	**Design Issues**	**Architecture Students (Bottom-up approach)**	**Innovative Design Students (Top-down approach)**
1st half of the class	Research and Analysis	Identification of Character	3.74 (well)	4.11 (well)
	Logic and Divergent thinking	Transformation of Context	3.58 (well)	3.78 (well)
2nd half of the class	Logic and Creative Thinking	Visual Element (+Identification of Character +Transformation of Context)	3.66 (well)	4.22 (very well)
		Composition	3.95 (well)	4.44 (very well)
		Mood	3.63 (well)	3.89 (well)
		Sensory	3.47 (well)	3.89 (well)
		Human Scale	3.68 (well)	4.22 (very well)
		Sequence	3.45 (well)	4.11 (well)

It is inquisitive that the results show that Innovative Design students, who learn in a virtual environment, outperform the Architecture students in all questions. This raises the question why these students are so confident. when looking at the responses to the open-ended question “How will you use the knowledge from Visual Training class in architectural design?”, Architecture students

emphasise the visual issues (character, mood, visual element, sensory, space, sequence, …), whereby Innovative Design students talk more about design process, variety of design, and new design. A qualitative approach seems necessary to find more answers to these questions, as well as to suggest how to improve future classes.

5. In-depth interview

An in-depth interview is used to answer the questions arising from the results of the questionnaire. The interview applies the same guidelines as the questionnaire. However, students are encouraged to give an explanation to the quantitative result from the questionnaire and let us find out why it was so. 10 Architecture students and 7 Innovative Design students were interviewed. The following results are supported by analysis of the teachers:

5.1. RESEARCH AND ANALYSIS

In the Research and Analysis part, Architecture students had to extract the character of an animal of their choice. They indicate they had to change the group -and the animal they analyse- so often that it discontinued their thinking process. It would have been better if they stayed in one group and analysed the same animal. Some students indicate a lack of analytical skill. Since some animals consist of so much information, they could neither analyse nor clearly organise their ideas, in order to provide a summary of essential information.

Innovative Design students were to imagine an Avatar World after they studied real-world information. Some indicate they didn't really like the research part at first and preferred to imagine out of thin air. However, they do belief that the research allowed them to know more and to create more realistic materials, whereas imagination only comes from existing knowledge and can be limited.

5.2. LOGIC AND DIVERGENT THINKING

In Logic and Divergent Thinking related to the transformation of context, Architecture students were asked to analyse the mutation of an animal due to a 1–7 degrees rise of temperature on Earth so the animal could survive in the new context. The students belief they did it quite well, apart from the class-management issue mentioned earlier. Most of the students had good logic and divergent thinking, as well as good imagination and creativity in storytelling. A variety of techniques were used such as drawing on paper or screen, dough- and paper models, etc. However, some students experienced limitation in making an understandable video presentation within the given time limit of 2 minutes.

Innovative Design students were asked to create an imagined Avatar World in the 3D virtual world as a movie set for their Machinima. They belief they had to change many things because of the limitations of the virtual world. For example, a rounded world had to be changed to a flat surface as they couldn't show the dark-bright side of the surface and couldn't adjust the gravity of the virtual world. They also indicate that, even though OpenSim provides substantial freedom to think and create, it is more suitable for a simulation of real-world objects than for an imaginary world.

5.3. LOGIC AND CREATIVE THINKING

In Logic and Creative Thinking a number of small assignments were given to Architecture students according the provided lecture (visual elements, sensory, mood, …). The students indicate this was too much work and that they didn't have enough time to complete a satisfactory concept. The assignment, that required students to incorporate many design composition theories simultaneously (i.e. creating a habitat for an animal using sequence, sensory and mood), created confusion. However, during the interview students could express their idea quite well using Visual Training technical terms. After a lecture in design composition theory, this was the first time they worked individually (they worked in groups before) and they lacked confidence as they did not have sufficient skills to put theory into practice. Some students also had problems in choosing the right material to make a model that best represented their ideas. Innovative Design students say they prefer the assignments on OpenSim because it was fun and less tedious then the assignments of Architecture students. They also enjoyed making the paper model as this allowed them to understand the differences between virtual-world objects and real-world objects. Even though their work seems to show an understanding of the issues related to design composition theory, they struggled with using the technical terms of Visual Training during the interview.

5.4. OPEN-ENDED QUESTIONS

Both groups indicate the knowledge they gained from the class was useful and that they will apply it in their future designs.

6. Comparison between the two approaches

The difference between traditional learning versus learning in virtual world can be summarised as followed:

1. *Reality vs. Imagination - media wise*: The learning objective of Architecture students was based on reality (an animal). Students think that physical models

have limitations in creating work and are tedious. The learning objective of Innovative Design students was based on imagination (an Avatar World). These students think that a virtual world is more suitable for real-world objects due to some limitations of the virtual world. From a teacher's point of view, physical models do have more limitations than virtual world models. Although it was a new environment, Innovative Design students took very little time to learn. They could create larger works with less effort in the same timeframe. They could also experiment with different ideas, shapes, forms and materials and subsequently were more confident in what they were doing.

2. *(Partly) disrupted vs. continuous creative process*: In both approaches the students learned to search, analyse and synthesise; the basis for logical thinking. Students created works from the same theme (animal/avatar world) during the three-step learning process, which is a continuous and relevant creative process. Even though the creative process of Architecture students was discontinued, this flaw is considered to be minor thanks to the continuous theme. On the other hand, Innovative design students had to work week-by-week towards the single-building exhibition pavilion for their Avatar World. The teacher realised that the work required substantial output and broke the work down into small successive parts for each week (case studies, conceptual design, design development,…). The Innovative design students were more confident in their progress and unintentionally learned about the design process.
3. *Poor vs. enhanced perception of space*: In the final project of the Architecture students it is found that physical models have more limitation than virtual models in terms of perception of space (especially interior space). Physical models were small and mostly allowed perception of exterior space and form, while virtual models allowed more freedom to explore both exterior and interior space.
4. *Real world Collaboration vs. Collaboration in virtual world*: Innovative Design students and teachers could freely collaborate during and after classes in the shared space via their personalised avatar. Architecture students were limited to meet in person with their collaborative partners. Innovative Design students also presented their work in the form of Machinima. Pedagogical value can be found in Machinima as a storytelling tool, as well as in how it offers a learning environment for collaborative digital media practices in the classroom (Lowood and Nitsche 2011). In our case, architecture became a background of the story that students recorded using their own avatars; a reason why they perceived it to be less tedious and more "fun".
5. *Bottom-up approach vs. Top-down approach*: the results reflect the different approaches of the two groups of students. Architecture students began with a small scale object (an animal) and developed their work into a bigger form of architecture (a pavilion inspired by the animal). Innovative Design students began with a very large concept and ended with architecture (an exhibition pavilion for the avatar world). Even though both approaches seem to meet the

same grounds, it is found that the work of Innovative Design students was relatively larger compared to the work of Architecture students. Innovative Design students could also give more detail to their works.

7. Conclusion and discussion

The different learning outcomes reflect the different approaches of the groups. However, the final design of the pavilion shows that both groups of students met the objective of the class. This does not conclude that one approach is better than the other but presents elements of reflection for lecturers who would like to explore a virtual-world learning environment.

Student's confidence has been mentioned all along in the above analysis. Architecture students seem to be confused at first but could express their work very well at the end by using technical terms. On the other hand, Innovative students were more confident as they developed step-by-step; they could experiment with different ideas in a virtual world and explored every detail of their work before submission. However, they lacked the skills to use technical terms. In future classes, visual elements and design composition theory should be emphasised to Innovative Design students, while the architectural design process is yet to be introduced to Architecture students. For next year it is recommended that Architecture students have more time to develop their concept of a single animal. For Innovative Design students it is recommended they have more small assignments based on the lectures about issues related to design composition theory. Emphasis should be given to their skills to communicate by using the technical terms of Visual Training.

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CAAD EDUCATION IN THE PANORAMA OF ARCHITECTURAL EDUCATION SYSTEM

A research on visualisation of the educational tools

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Abstract. The significance of CAAD begins with tools. However, the values of CAAD to architecture education are not only in increasing subjects associated with CAAD in the teaching but in improving comprehensive digitisation of architecture professional education. When CAAD develops into the level of BIM, the value of information emerges. And as the exchange mechanism of build information share data at the same time, BIM already has User-Facing Exchange Models and Vendor-Facing Model in NBIMS. Educators are more sensitive to the happening process of professional education and BIM should and can have Education-Facing Model and two inferences about the comprehensive digitisation of architectural education system including the visual organisation to architecture knowledge and the establishment of teaching process management digitisation system for whom a direct derived research is the application of AEIM (Architectural Education Information Model). This paper is a preliminary study of the possibility of such a model and its value as a tool of design education, and further research can be conducted to study the systematic structure of the information model and methods of its visualisation.

Keywords. Architectural education; education information; BIM; information exchange; visualisation.

1. Introduction

The study of CAAD education should include specific teaching methods and also the existence status and development of architecture education system. Architectural education has its own subject system including targets, contents and methods.

The architectural education with the cultivation of professional architects as its basic goal and "education based on problems" as basic education idea can include three main education contents, namely, "issues of architects, of building and of architecture".

"Issues of architects" is actually issues of architectural design including the content of "design tools training" and CAAD is one of the tools of modern architectural design. CAAD develops as a design tool and gradually changes the paradigm and organisation method of design as well as the way how architects see architecture design as a subject. CAAD itself gradually develops into "digitisation design". At the current stage of CAAD development, people finally become aware of the value of "information" and have BIM to describe buildings, eventually extending the meaning of CAAD itself.

Meanwhile, CAI has been widely used in education, too. With the comprehensive promotion of digitisation technology, CAI will combine with the modern educational technology and evolve into the application of CBE (Computer-based Education). At the same time, when CAD develops into digitisation design, it may also evolve into CBD (Computer-based Design), which may include BIM application, BIM data exchange standards, BIM education development and BIM & BLM (Building Lifecycle Management) integration etc., all being the informationisation of design.

Under such background, the digitisation development of architecture education has two main clues. One is study of teaching and learning methods of CAAD and the other is the visualisation information organisation of architecture education with modern education technology, and the comprehensive digitalisation of the management of education institutions.

2. CAAD Teaching in Architectural Education

The teaching and exercise of all sorts of design software are the most basic and intuitive composition of architecture digitisation teaching. However, the significance of digitisation to architecture professional education goes beyond that and the teaching methods of software tools are different from that of the traditional tools.

In the professional training tutorial, that "students learn tool use through the design training" is the general opinion. On the other hand, more positively,

CAAD can serve as teaching tools, where teachers or teaching system can "teach architecture, building and designing principles through the digitisation tools".

Tools system integrates design knowledge, goals and methods and students' understanding of buildings, experience of designing and use of tools are mutually influenced and happen at the same time. To master the using skill of design tools is only a branch goal of professional education and the fundamental purpose is to research architecture design through the design tools.

2.1. TOOLS OPERATION TRAINING OF VOCATIONAL EDUCATION

Among the series of courses relevant to CAAD education, professional tool training comes first in architecture professional education.

Any vocational education for the labour reproduction in the industry behaviour has "labour tools operation" training subject to educate. The training methods is practical and mature tools system also integrates major professional objectives and basic rules.

Generally, CAAD tool, in terms of design, can be briefly divided into "modelling" and "simulating", two types of technical tools oriented to the comprehensive performance design of building. To extend, if the two components of modern architecture (academy and practice), namely, "environmental behaviour" and "environmental control", are agreed on, modelling and simulating of digitisation tool are right corresponding to the basic goals of contemporary architecture.

Digitisation modelling tools, just like art methods, is a classical architecture design tool. Take parameterised shaping research for example. It does not just "create" or "produce" new shape aesthetics outside general life experience, but is to guide students, at the level of architecture education, to study the "possibility" of shaping including the linear and nonlinear. Parameterised shape design tool has a certain limitation, since it is a pure shaping study detached from human behaviour or humanity factors, so it still falls into classical architecture.

Digital simulation tools are related to technique-related subjects of architecture, and it is especially used for the teaching of green architecture design and building performance evaluation. Nevertheless, CAAD tool needs to integrate comprehensively with traditional subjects, such as the material and structure course based on BIM (such as Revit), graphics course based on modelling tools (descriptive geometry and shadow perspective), building physics, to name a few. These courses are easier to set up at a lower cost.

If we perceive the value of traditional tools in the sense of "modelling" and "simulating", we can see that traditional design tools appear to be some

skills about architecture art, but in fact, architecture art techniques are modelling and simulating too in shaping study of physical building and its space design. We may even find that the traditional "tools training" approach, originally a "visualised" means, is running by integrating special subject training with subsequent circular practice (in design course). Early use and teaching of CAAD also followed the work mode of art tools, such as AutoCAD and SketchUp, which, like paper, compasses, pens and rules, shared the common property of "general-utility tools". They can be mastered by the educational level coequal with high school and are kind of "body memory" skill.

Compared with the traditional "general-utility tools", current digitisation tools for design are professional "customised tools", which integrate more professional goals, rules and methods. Digitisation tools have higher level of integration of the professional behaviour and the establishment of "tool-use skills" needs to be based on more comprehensive specialised knowledge.

Therefore, professional architecture education needs to help students to gain comprehensive and systematic knowledge of the specialty via the use of tools. In this sense, the essence of "pedagogic rule" of digital tools does not lie in "learning to use the software tools by designing practice (design assignment)", but in "learning architecture and design via the designing tools". And this is what digitalisation technology really means to the architecture education.

2.2. THE SIGNIFICANCE OF DIMENSIONS OF DIGITISATION TOOLS

Design associates with goals via tools, and goals and tools are mutually influenced and restrained. Meanwhile, goals and tools also develop synchronously, and the number of dimensions of digital tools is close to the comprehensive information description of the goals. Form-oriented "geometry modelling" software differs from design-oriented "information modelling" system, in that they concerns different level of dimensions.

Digitisation tools are generally considered to be a system concerning three dimensions. But if 3dMAX and other big and perfect modelling tools are used only to render graphs in practice, the final number of dimensions would be less. On the other hand, although the use of 3D tools will alter some terms in the traditional design concept, such as plane changed to function, section to space, elevation to form, sit plan to environment, which even implies that drawing as "design achievements" may be surpassed, 2D graphics operation method, however, is still effective.

For example, the Revit system based on the idea of BIM is not meant for 2D graphics but it does not reject to work in 2D space and each operation of "back to 2D" is to make necessary dissembling of three dimensional

space in order to isolate the irrelevant data or information. The 3D Shaping and Viewing management ability of Revit is almost the same with SketchUp, but its operation process is accompanied by more follow-up work information, which shows the significance of BIM in perfecting the dimensions of construction information. The design by using BIM and extended tools will no longer be stuck with the issues of production drawing, but will focus on "design for construction".

In this sense, the development of digitisation tools is not a simple leap from 2D to 3D, but is three-dimension beyond simple geometrics, having significance in managing the whole "design-construction" process in time dimension.

When CAAD develops into digitisation tools, it is more than just a CAAD software product, but an integration of a series of related tools corresponding to each gradual goal in design process and a series of related subjects in the professional education. Just as each design or each house includes all the issues in architecture, the teaching and learning of digitisation tools need to be comprehensive, systematic and penetrate into each subject, and need to help students to form the concept of BLM in architectural education.

3. CAAD promotes the digitisation of the information resource of architectural education

In the concept of information, information quantity varies at three different levels, namely, "informationisation, digitalisation, and quantification", with that in informationisation being greater than in digitalisation, that in digitalisation greater than in quantification and quantification is the most stringent informationisation. There are still elements in architecture that can't be quantified, but can still be digitised and informationised. CAAD gets into development as a quantifiable design tool and its training is added to professional education. But tool training solely does not make the whole of professional education.

When CAAD develops to the stage of the introduction of BIM, the concept of information is highlighted. The value of information regarding architecture research and its education research brings bright prospects.

3.1. THE VALUE OF THE CONCEPT OF INFORMATION IN ARCHITECTURAL EDUCATION

Digitisation is the study of information in essence. When "information" works as a basic "observation method" to architecture, it will help to get a completely new understanding of the traditional concept of architecture and to make clear the logic order of prevalent concepts.

In fact, the wide existence of digital information changes traditional idea and behavioural habits of architecture design. As a result, architecture design has already been a process of information processing.

Part of the basis of architecture design and architectural education defies digitalisation, but it is still effective work information. Quantification is the strictest at the informationisation level, just like various data in professional regulation. Various information systems are also management systems and the management operation object is all kinds of information or, information is the intermediary to manage things and processes. At the level of digitised information, design may as well be perceived as the study of construction, and the excavation, managing and processing of construction information.

The concept of information is of great significance in the study of various issues in architecture education. The goal of architecture professional education is to cultivate the ability and ultimately form the working style of architects. "Issues of architects" are to help students eventually learn the "professional working mode of architects", including the architects' way of dealing with comprehensive construction information in various media.

"Issues of building" are expressed by BIM system now. As a digitising, visualising and structure-systemising information model, it includes the quantifiable part of construction information such as material, structure, spatial scale and codes of practice. Beyond BIM, we have put forward the possibility of SIM (Space Information Model) existence as a kind of coupling type gestalt work (Zhang and Wang 2010) to promote the study of perception behaviour in space. As to "issues of architecture", its digitisation calls for continuous exploration due to the existence condition and complexity of the general knowledge hierarchy in architecture. The digitisation of existing concept in the subject is relatively easier, such as the completed work on IFD.

For architecture education, however, the multiple relations and logical sequence of various concepts (including technical and humane, spatial and behavioural) are more important. Researches find that the link between concepts is neither linear nor 2d, but some kind of "N-dimension space system with many subsets". An effective software tool is required to deal with this "system of architectural concepts", and this is, to some extent, the requirement of architectural education on CAAD system development.

3.2. BIM LINKED WITH BLM UNDER THE CONCEPT OF INFORMATION

With regard to the management value of digital tools to design-construction process, needless to say more, the study of BLM has already been conducted. This is a concept with ecological significance, which can give a more profound insight into building and the professional behaviour of architectural design. It

should become one of the basic professional concepts of the contemporary architecture graduates. When BLM is connected with BIM, as is easy to see, the Ms in "Model" and "Management" can help to understood each other, that is, besides the original meaning of BIM (Building Information Model) and BLM (Building Lifecycle Management), "the process of design" is "the Management of construction information (BI-Management)", and "the result of design" is to get some "predictive Model of building lifecycle (BL-Model)".

The academic research and teaching application of the related issues of architecture digitisation should also be based on such basic understanding.

In fact, the types of special tools of architecture digitisation correspond to all phases of the lifecycle of building (or the lifecycle of design). The discussion of relevant teaching methods can take "the time sequence of digitisation tools entering the design process" as one of the research topic and provide reference for the organisation and management of the production and practice of the architectural engineering design, by researching the organisation methods of architectural design courses. In fact, the organisation methods of the two processes can be cross reference.

4. Visualisation of architectural education information in the concept of BIM

Even if based on the same architecture discipline knowledge, principles, methods and tools, professional education and vocational practice differ in goals and processes. BIM system is mainly researched and developed for professional practice and takes building information description, information exchange and production organisation as the core. On the one hand, although BIM is not intended to be a specific design tool, but the tool system based on the BIM idea (such as Revit) provides a kind of data structure to describe building system, known as the organisation structure design of the software menu, gradually familiar to software users. On the other hand, studies are being conducted about BIM as a share data exchange mechanism of construction information, including organisation methods of data structure, such as the ongoing work of *The National Architecture Information Modeling Standard* (National Institute of Building Sciences 2007). A direct derived research of this study is the presentation AEIM (Architectural Education Information Model).

BIM already has User-Facing Exchange Models and Vendor-Facing Model in NBIMS, and educators must be more sensitive to the happening process of professional education. Therefore, BIM should and can have Education-Facing Model and two relevant corollaries of "Comprehensive Digitisation of Architectural Education System" including the visualisation organisation

of architecture knowledge and the establishment of the digitisation system of teaching process management.

4.1. SYSTEMIC ORGANISATION OF THE EDUCATION CONTENT

Enlightened by BIM and as a speculation and extension of BIM, AEIM (Architectural Education Information Model) is the study and expression of the architectural knowledge system. The system of AEIM (Architectural Education Information Model) is set up according to the special requirements of professional education, which may include logical organisation of professional knowledge and the establishment of the intrinsic connections between concepts. The R&D thought of this system takes basic cognitive process and education goals as the core. In fact, the R&D technology of BIM and the hyperlink technology between web pages have been the technical template of AEIM system.

The textual information of architectural education, in a narrow sense, refers to the "thought, history, theory, knowledge, principle, method" of architecture issues, which are present in theory courses and are knowledge components of architecture to some extent. It's textual and relatively static. The textual set of concepts can at least be digitalised and informationised, if not quantified. In fact, the appearance of BIM is right beyond the restrictions of early CAAD tools on quantification. In generally, there are two main aspects in architectural education, namely, architectural design courses and architectural theory courses. Theory courses are not the specific design ability itself, but are needed in the design process as basic subject cultivation and serve as the knowledge basis of design innovation. The aim of the establishment of AEIM is to promote the integration of design courses and theory courses.

At the level of keywords, the system of AEIM meaning will establish the (visual) connections between key words and overtake the established structures of traditional courses and subjects, and may well change the forms of traditional teaching material. In this sense, the study of architectural education is also the study of architecture itself, in which there may appear advancing research propositions, such as the study of "knowledge discovery" in architecture. AEIM will be conservative as well as open, and a continuous maintenance of AEIM will accumulate the value of conservable part in architectural education. AEIM faced with students can provide a panoramic cognitive map of the subjects, which can be seen in AEIM software menu interface.

4.2. THE SIGNIFICANCE OF VISUALISATION TO THE THEORETICAL TEACHING OF ARCHITECTURE

The reason why AEIM is put forward as a hypothesis or inference is owing to the awareness of the concept of computer visualisation and the development

of its technology.

In fact, architectural design has all along been done with the visualisation method. The art method is the most primitive and most direct visualisation. It can even be realised that the development of the architectural design tool system is right attributed to the continuous advance of "visualising ability of tools". It's not because the design object is substantial and with concrete shape, but because visualisation can aid thinking intuitively in the design process. And this is the key to the question.

The "implicit" thinking activity in the design process, either analytical or synthetic, needs materials to analyse or synthesise; design innovation is firstly thought innovation, stemming from the processing or disposing of the existing concepts.

Architectural knowledge, principles and theories are the basic material for the design conception, converting to the designers' professional background. The education information composed of knowledge, principles and theories contains graphs, text and data, etc., and can be further divided into graphics primitive, terms, principles, formula, etc. among them, the conservative, stable and static part is the basic components of the discipline, which takes the form of a series of "subjects" and is stored in the principles or theories in the textbooks.

However, the storage of text information is one dimensional, and the connections between concepts and the production of meaning have to be achieved via reading. This is the drawback of text in terms of dimensions when used as a tool of thinking. For example, in *A Pattern Language* (Alexander et al. 1977), in order to overcome the barrier of linear text, the book offers the context of every pattern in the whole pattern system of the book, so as to establish connections between different modes. This is the most primary mode of mind mapping. It can be imagined that today's version of *A Pattern Language* will take more direct and exquisite visualising expressions. In fact, that is the method we adopt when guiding students to study this book.

Concepts are meaningful only in the connection system. Visualisation method, as is assumed in AEIM, expresses concepts as a direct, connected and panoramic mind mapping, making theory learning and design conception an "explicit" activity in a degree. This is the meaning of design tools in aiding thinking activities. The thought processing of concepts is an operation to the non-quantifiable information in architectural design, which is beyond the traditional CAAD tool. Digital information is information instilled with energy. The visualisation of such power-driven information is real-time and dynamic, aiming at establishing multi-connections between concepts, while the thought activity itself is dynamic, active and sometimes unpredictable.

The awareness and using of AEIM have actually existed subconsciously and occasionally in the practice of design education. Converting the subconsciousness into conscious and explicit research subject is right the life prototype of "knowledge discovery", where the "hypothesis & verification" process is the basic way of academic research. The conjecture of AEIM is, apart from scientific study, the product order made by architectural educators to the software providers.

5. Conclusion

This paper is not intended for specific teaching method of CAAD. It advocates the education aim of protecting and cultivating students' innovation. However, if the emphasis on innovation was confined to "moral preachment", it would be the "educators' bluff". Practicable innovation requires innovators possess basic specialised knowledge and master the operating skills of professional tools.Besides, all vocational education has the duty to train practitioners to use professional tools and advanced tool system needs more specialised knowledge as a basis. In the basic education of architecture, The dissemination of knowledge, even if it's only for the use of design tools, is important; while the efficiency and effect of the dissemination is restrained by teaching methods and tools. AEIM is put forward for the development of the tools and methods of architectural education.

A definite research goal will help the allocation of academic intelligence, so as to boost the academic development. The teaching research of the architectural digitalisation, not confined to the use and teaching methods of CAAD, is a comprehensive digital upgrade in contents, organisation and institutional management of architectural education. In the background of the Information Age, the teaching research of CAAD coincides with the study of architectural education, while the latter is a systematic study of architecture, with digital methods and technology as the most effective tools, among which "information model" and "visualisation" are the most typical methods.

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CROSS POLLINATION OF IDEAS

Design fabrication and experimentation

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Abstract. The following pages show a selection of studio projects which explore the opportunistic collaborative process between commercial fabricators, material sponsorships, and the institution. The articles speaks about the intersection of design experimentation and significance of fabrication within the contained process of [*design* | *optimisation* | *fabrication*]. Within this process the article intersects between practice, commercialisation, and design-research, into the development arena of architectural academic outcomes. The demonstrating fact within much of the research and development also touches upon intricate details of modularity, and designing with *optimisation* in mind for the purpose (and ease) of fabrication, prototyping, and 'real-life' production. While the focus of the academic studios deliberates and uses parametric design systems through digital and analogue modelling to contribute to a full scale designed installation, and actively working with a commercial fabricator and material sponsor (Luxx Newhouse & LG Hausys HI-MACS). The aim of the courses were to acquaint students with theoretical and practical conditions needed for the creating of experimental relational modularity between geometry, scale, and materials as well as the ability to negotiate between quick intuitive studies and definitive quantifiable decisions.

Keywords. Design fabrication; material investigation; industry collaboration; architecture; industrial design.

1. Cross-pollination of ideas

Whereas academia used to be considered the breeding ground of 'new' ideas and innovation within the architectural practice – having the allure as an

incubator of innovation with access to fast processes of tools and techniques and a think-tank mentality – the developmental nature and spotlight of the practice has now shifted itself from academia back to practice. Within the past few years, students and industry has combined forces to nurture developmental research within the processes of physical prototyping and fabrication methods, or have transferred their focus to seek research based collaborations with commercial (sometimes even corporate) and small design-research studios for inspiration. By seeking assistance from practicing and specialised practitioners of the field – most beneficially with industries outside architecture, like industrial design – architectural education could further prepare students to situate and incubate their research as a breeding ground for alternative methods of making and digital crafting for the built environment.

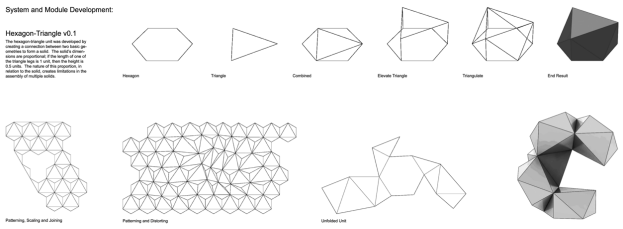

Figure 1. Systematic output from Digital Model to Analogue (Physical) Prototype, image provided by Thomas Kieper.

Academic collaborations with practice are nothing new. Think-Tanks and NGO groups have worked with many well-known institutions such as the Harvard Business School, Columbia Business School, and the Woodrow Wilson School of Public and International Affairs at Princeton University, just to name a few. Industrial design brands and automobile companies have also, for many years, established opportunities of incorporating research and development studios within the academic setting in Europe. A delicious example between the intersection of academia and practice is the RPI (Rensselaer Polytechnic Institute) and SOM (Skidmore Owings and Merrill) alliance. Established in 2008, RPI and SOM brings together the interest between academia and professional practice giving birth to CASE "CASE Center for Architecture Science and Ecology" (2011). In this particular instance, the joint venture between the School and the Practice (RPI + SOM = CASE) becomes a mutual benefiting collaboration of ideas and learning experiences.

Since 2009, the Massachusetts Institute of Technology (MIT), working under the name of Massachusetts Institute of Technology Energy Initiative

(MITEI) "*Massachusetts Institute of Technology Energy Initiative*" (2011), has issued a joint venture between *Masdar Institute* (a tri-fold initiative between industry, government and academia) "Masdar Institute" (2011), which researches closer within the means of the sciences and engineering of integrated sustainable development and energy technologies. Yet, whether due to financial or feasibility issues, other than the research and development on alternative and renewable energy technologies and solutions, the probability and the larger intention of cross-pollination between the academic and the construction practice still needs to come out of the woodwork.

Recently, in collaboration with Luxx Newhouse Group[1] and LG Hausys HI-MACS[2], and a group of six students participated a summer studio lead by the author and co-instructor Prof. Marc Aurel Schnabel. The summer studio aimed to acquaint students with theoretical and practical conditions needed for the creating of experimental relational modularity between geometry and materials as well as the understanding of scale within architecture. The study and work was a hybrid crossover between architecture and art, with a high concentration on the developmental nature of experimentation and detail. The two projects process emphasised the analogue as much as the digital, along with a methodological design approach, between context and technique that is implicit in the process of design and integration of site.

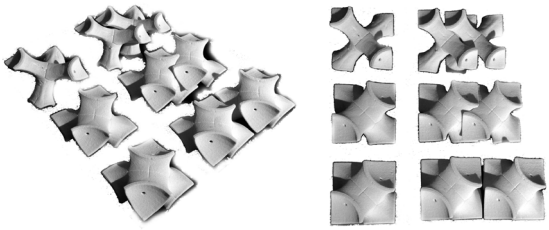

Figure 2. CURVAR Modular Prototype A, Individual Modulars – Variable Modulars, Image provided by Michelle Lok, Marco Chan, and Ivan Cheung.

The students were asked to develop investigative design methodologies with potential prototyping capabilities working together as two teams, one team investigated the potential outcomes of an internal application of modularity within an interior condition and the other team concentrated on a design process considering an urban external condition designing a piece for exterior application. The production of the piece went through multiple iterations, while the students had the opportunity to work directly with the technicians within the factory and fabrication facilities, to learn the importance of pro-

duction and fabrication in the real-world environment. The final piece is still under construction and is slated to be exhibited in Shanghai, Singapore, and Hong Kong Shenzhen (HKSZ) Biennale.

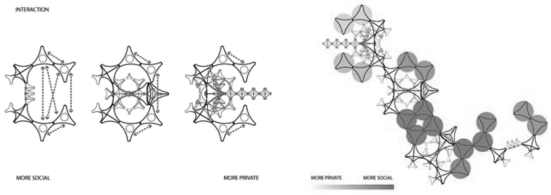

Figure 3. TETRA Modular Prototype A, Installation Organisational Diagrams, Image provided by: Kenneth To, Kathleen Johnson, and Dave Cheung.

The focus of the studio investigated the use of parametric design systems through digital and analogue modelling to contribute to a one-to-one scaled prototype for a larger built system. For the students, the difficulty of utilising the computer as an active part of a design process is to interject the ability to negotiate between quick intuitive studies and definitive quantifiable decisions. The interpretive model is the design space within the workflow where ideas can remain separate and abstract. As relationships between the parts in your design coalesce, a new type of workspace is formed which deals primarily with associations of the parts and their interdependent relationship with the whole.

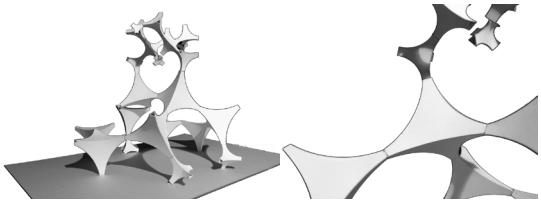

Figure 4. TETRA Modular Prototype A, Overall 1 – Detail 1, Image provided by: Kenneth To, Kathleen Johnson, and Dave Cheung.

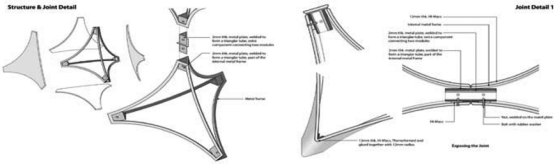

Figure 5. TETRA Modular Prototype A, Joint and Structural Detail 1, Image provided by: Kenneth To, Kathleen Johnson, and Dave Cheung.

Meanwhile, the studio also used the facilities of a fabrication lab within the school (smaller tooling – i.e.: vacuum forming and laser-cutter) and commercial (larger machines – i.e.: silicon thermo-former flat-press and 6-axis CNC mill) context, which allowed the research to be evolved from the abstract speculation into very specific production experiments and project. The student teams were responsible for choosing one method of design and investigating different types of installation and material/fabrication methodologies. The greatest challenge within the studio was to determine different assembly strategies, structural systems, and aesthetic effects, through the use of a significant amount of physical experimentation.

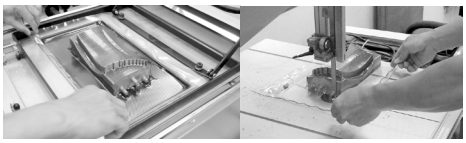

Figure 6. CURVAR Modular Vacuum Forming Process / Prototypes A (Transparent PVC) / Prototype B (Opaque PVC).

With the institute's ability to mobilise large groups of educational entrepreneurs and spouting youthful energy from the student body, the opportunities between academic and practical joint ventures are endless. Yet, the question still lies on whether the practical building and construction industry has viable interest and development utility for architectural research and development for the building industry.

2. Intersected collaborations

Similarly to the academic exploration of the summer studio, an outlet from architecture could be found within my research and practice where there is an active convergence to engage the industry within my work – many times through the experimentation with industrial design and fabricators outside of architecture. Through engaging industry outside architecture and design, the designer benefits through professional advices which are not inherit to the architectural trade itself, but allows outlying professional techniques to be applied into mutual intersected explorations of innovative means of attaining the same goal, in or outside of architecture.

For example, with the project of the *Cross Fabricated Scales* Wall Modular – originally spawned from a design commission of a 7,500 sq ft office design project in Hong Kong – became investigative and collaborative journey working with both *DuPont Corian* and *LG Hausys HI-MACS*. The commercial project interjected the opportunity to better understand the 'real-life' applica-

tion of solid surfaces and acrylic based plastics from a research and experimental perspective, which simultaneously reacted to the industries needs into the realised project. For HI-MACS and Corian, the traditional application of the material was for countertops and sinks, whereas for the basis of academic design-research, the design exercise became a challenge and occasion to apply the solid surface material as either 1) a wall modular, or 2) as a dynamic cabinetry system that seamlessly continues within the workspace.

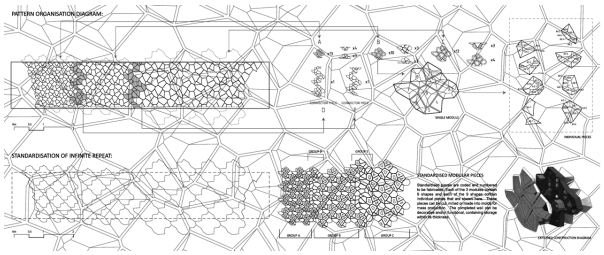

Figure 7. CFS Wall Modular Prototype A (Physical Model – Individual Pieces), image provided by Wendy W Fok.

Figure 8. CFS Wall Modular Prototype A – Process of Assembly, Material: LG Hausys HI-MACS, image provided by Wendy W Fok.

By establishing these active networks with the industry, the relationship between academia and industry becomes a unique synergy of significant contributions and contacts within an integral pedagogic approach. The ability to incorporate those same industry partners and sponsorships into an active milieu within academic studios become an imperative departure to the education of architecture. Collective learning and operational collaborations in exploring the scholarly journey and discovery of architecture and design, through the process of making, therefore, becomes an expansive base of design-research opportunities that surpasses the traditional research and development education within the classroom setting.

3. Architectural making and education of fabrication

Pedagogy, Research, and Practice should be understood as mutually catalytic. Architecture has become both a profession and an art that continually engages

the multiplicity of socio-economic, sustainable and cultural concerns, and more recently, accesses a variety of technological advances for fabrication, material production, and generative digital organisations. Architectural education has thereby become a normative, focused, yet exploratory field of design-research, engaging the advancement of investigations through design processes facilitated by the inquiry of skill-based training of the technical and academic curriculum. Essential to any field of design is the ability to extract and interpret abstract data from a field of sources. Architecture thus proves the importance of an active appetite for theoretical references of architectural history and philosophic jargon, yet does not allow the process of design to purely react to solely theoretical research. This brings to the point that architectural design and education should inherit a process of making (analogue) – making in terms of fabrication through experimentation and making through the processes of physical investigation past the digital (virtual) computational means. Though, fabrication itself should not be considered as purely 'just' an act of making, but, where making becomes and functions as a critical thought process within the contained process of [*design* | *optimisation* | *fabrication*]. Within this process neither steps are branded as a fixed process, but considered as a process which could be materialised through an informative feedback complimentary to each other.

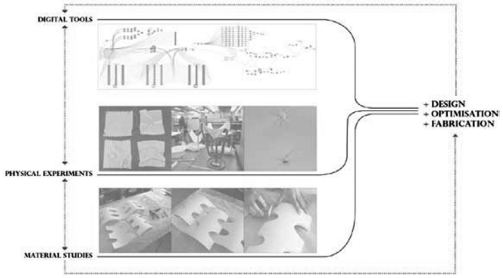

Figure 9. Diagram of contained process of [design | optimisation | fabrication], image provided by Wendy W Fok.

4. Action of making within practice

Reiser and Umemoto (2006) in "Atlas of Novel Tectonics" gives a pointed statement that the "*Material practice is the shift from asking "what does this mean?" to "what does this do?*". This crucial comment questions the genesis from interpretation and meaning to performance in architectural thought, moving beyond the instrumental notion to point from a shift from meaning or value to performance or function, beyond traditional critiques that operate within metric spaces. With digital architecture's ability to fascinate due to its visual stimulation and novelty, the saturation of advanced computational tech-

nology has clearly become available to anyone that can participate in the field through the use of digital tooling – a scope and scale of which was unavailable to people even just one generation back. By simply a click of the mouse button, people of diverse backgrounds and experiences can explore, innovate, and contribute to an ever-growing community of designers, each one with their own methods and desires. Posing the question on how our visions of objectivity, as architects, could diverge with various tendencies pushing on our understanding the limits of different material and analogue (physical) properties to further the development of architectural design.

As an augmented quantity of designers incorporate diversified parameters into their projects, an increased number of potentials within formal creation emerge; equally, as an increase in the techniques of application become available, maintaining a coherent narrative of the creation process becomes progressively more difficult to maintain as continual, real-time inputs from a variety of sources can easily turn into an cacophony of discordant voices each ripping apart what another has tried to join together. Thus, we see the fundamentality of mapping a layered approach within "design intelligence" between parameters and constraints which simply becomes the decision and knowledge accumulation incorporated through organisational efforts disposed by the architect.

Speaks (2002) has once termed "design intelligence" as a process of which "[m]aking becomes knowledge or intelligence creation. In this way thinking and doing, design and fabrication, prototype and final design becomes blurred, interactive, and part of a non-linear means of innovation." Within this process, "design intelligence" is taking the opportunity of design to the level of one-to-one scaled model-making and prototyping, and surpassing the possibility of transitioning between *design* | *fabrication* and past the processes of *optimisation* ingrained within the process of design. Fundamentally speaking, the ethos of embracing digital fabrication within the architectural practice and design processes is to strike an opportunity of generating materials within the experimentation process (or, the contained *design* | *fabrication* | *optimisation* process), which becomes a laboratory of opportunities. These potentials for creating an optimisation for an enhanced fluidity between the design and construction could interject for either 1) a productive pre-testing ground of feasibility design analysis for the ease of further discussions with the sub/contractors and fabricators, or 2) utilised as design developments and experimentations on smaller scaled prototypes into creating junctures grounding propositions past the schematic phase within the design process.

As discussions continue to propose the difficulty of utilising the computer as an active part of a design process, designers begin to further the ability to

negotiate between quick intuitive studies and definitive quantifiable decisions. These interpretive models then alter the design processes where the workflow of ideas can remain separate and abstract. As relationships between the parts in design coalesce, a new type of workspace is formed which deals primarily with associations of the parts and their interdependent relationship with the whole. Concurrently, projects will require exploring the rigorous design methodologies that trace the developments of complex and dynamic forms in the context of their structural feasibility. While, the evolutions of topologies are of special interest, typological properties intrinsic within the technique of design will also be placed in consideration. Thus, in order to understand of "*what does this do?",* the practice of architectural design, surrounded by investigative and re-combinative form finding processes and evaluation, should entail sustained lab testing of physical models within the systematic development of understanding both 2D and 3D modelling, in conjunction with computer simulation and the optimisation process.

5. Digital relief and fabricating the future

Digital tools should be looked upon as a method to further but not replace or surpass the designer's ability to interject the interpretational process from vision to reality. While the fabrication process could be limited through the techniques applied onto the fabrication by the production tools, the ability to examine with an iterative process by physical experimentation, through thinking critically, should transcend the creative process. Moreover, through the experimentation and the iterative processes of prototyping, and experimentation of multiple materials, the ability to formulate coherent methodology could be further refined and developed, both physically and theoretically.

The ability of digital design and alternative methods of fabrication delivers, on one hand, an approach to harness the computer as a generative medium for design, while on the other hand, assesses the versatility of material experimentation within the architectural design process through one-to-one scaled prototypes. Within practice, design, and education is the ability to challenge the dynamic significance in structuring and mapping the ideals of art, architecture, and urbanism, contained by the process of making. By utilising the synergetic methods of digital and analogue fabrication as a means of full scale design and dynamic analysis, the convergence of digital design and fabrication will continue to address the late Robin Evans' concerns about the relationship of social and spatial arrangements while operating within the understanding that physical experimentation becomes a process of discovery.

Moving forward, the potential of fabricating the future is not only to understand the formal approaches of design, but should be toward investigations of

contextual and content-related natures of fabrication, along with cradle-to-cradle[3] material investigations that compliment scaled prototypes within architectural design. Although digital (virtual) investigations through computation is valuable in term of analysis and fundamental testing, analogue (physical) fabrication and prototyping alleviates the masking contained within virtual realities, which releases discussions within underlying ecological principles and material investigations. While our position as educators and designers should continually push the boundaries of digital design and manufacturing as a means of closing the gap between the intersection of architecture, practice, and education.

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Endnotes

1. Luxx Newhouse Group Pte: fabricator of solid surface materials located in Asia, with factories in Singapore and Panyu China.
2. LG Hausys HI-MACS: HI-MACS® is the Solid Surface material. The mineral material consists of approximately one third acrylic resin (polymethyl methacrylate or PMMA) and 5% natural pigments. Its main constituent, with 70%, is the natural mineral aluminium hydroxide (ATH) obtained from bauxite (aluminium ore).
3. Cradle-to-cradle Design: (sometimes abbreviated to C2C, or Cradle 2 Cradle, or in some circles referred to as regenerative) is a term originally termed by German chemist Michael Braungart and U.S. architect William McDonough. C2C is a biomimetic approach to the design of systems.

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PROCESS-DRIVEN CONCEPTS

Digital agendas in studio teaching

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Abstract. This paper discusses studio design curricula using digital design as the medium to design process. The fundamental idea explored is that digital design thinking is fundamentally process driven as opposed to narrative driven and that digital design thinking leads to different way of conceptualising and solving design problems. The paper presents four studio case studies using different methodologies illustrating current digital design models. The types of studios chosen and the working methodologies adopted will be discussed in the light of understanding this shift of design conceptual thinking.

Keywords. Digital design pedagogy; digital conceptual thinking.

1. From form to process – a change in architectural conceptual thinking

The conventional educational model in the design studio has generally employed accepted a simulation of praxis as a didactic model. That is, most studios still employ stages that are usually driven by an interpretation of program, site, and conditions carried through stages of conceptualisation, schematic design and design development. Since the 90's designers (Lynn 1999, Aranda and Lasch 2006, Liu 2005) started to define paradigmatic approaches in architecture design education, and as a result architecture as a design discipline changed methodologies, the notion of "processes" being more interesting than "ideas" (Zaero-Polo 2003) for example was a key change to design thinking.

Extensive research into digital pedagogical models and techniques and their relations to studio design has been developed by various researchers as a foundation for design education and pedagogy (Knight and Stiny 2001, Frazer 2002, Kvan et al. 2004, Oxman 2008). From these studies and frameworks

emerged the formulation of digital design models in studio teaching, the conceptual content and vocabulary of digital design. In their research the transition and transformation of concepts such as representation, precedent-base design and its replacement by concepts like generation, mutation, animation, and performance-based design and behaviour was solidly demonstrated (Lynn 2003, Kolarevic and Malkaawi 2005).

2. Four process driven studio methodologies

In this paper the four studios have been categorised in: "formation", "generation" "performance" and "behaviour". These themes arise from observation of current digital trends in education in the UK and are meant to facilitate a distinction between digital approaches and learning methodologies. This distinction is not to be taken rigorously as some of the studios overlap in tools and theoretical philosophy (for example both "generation" and "behaviour" share emergence, self-organisation principles). Ultimately, the themes represent the growing interaction between architecture and computer science, biology, robotics, artificial intelligence, electronics among other areas; they represent driving digital concepts and it is not intended that they suggest a classification for a digital pedagogical framework. The four design studios case studies presented in this paper were taught at different levels in architecture education using different conceptual digital design approaches. The first case study is at undergraduate level (year 2 and 3 in a vertical studio), at the Architectural Association by Claudia Pasquero and Marco Poletto. In this studio brief students have to develop and apply dynamic mapping and real time simulations as a design methodology. The second studio case study in 4th year studio in Canterbury Architecture School, UK by the author of this paper. This studio uses L-systems as an organisational generative design tool for designing a university campus master plan in a derelict industrial zone. The third case study is at a post-graduate level at the Bartlett School, UCL at the Adaptive Architecture and Computing MSc by Sean Hanna. The studio uses optimisation and machine learning techniques for structural design and digital manufacturing. And finally the fourth case study at an undergraduate level, 3rd year Interior Architecture students in Canterbury Architecture School, UK by the author of this paper. This studio uses Physical Computing techniques to explore adaptive and responsive space. In the next section of the paper each studio's methodology and outcomes are described.

2.1. "FORMATION"

Studio #1: dynamic mapping and real time simulation

The design methodology puts a great emphasis on the material, spatial and

temporal articulation of outputs for social organisation and physical production. The design process is made through plans, sections and detailed drawings that form the basis to investigate the critical intersection of the design outcomes.

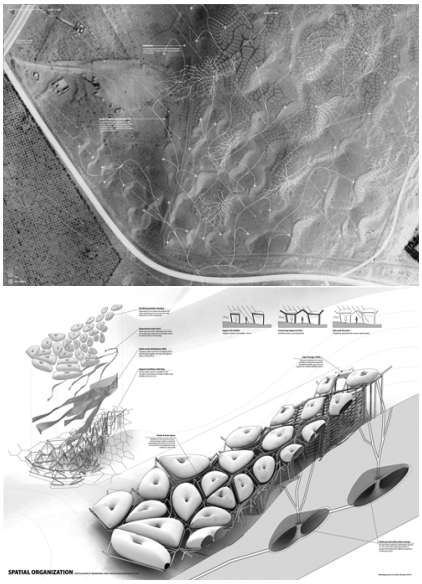

Figure 1. INTER10_ Re-charging city_ solar desalination dune,. AA Unit 10 Intermediate 2010.

The digital drawings form the basis for all the studio design investigations; students acquire the necessary digital design skills to produce the digital drawings. A first set of drawings operates as frames to manufacture the productive landscape models; a second set, more detailed, will describe physical prototypes models. Outcomes: The *Prototype models* are not representational "maquettes" but are fabricated and deployed as tools of experimentation; they are treated as generative prototypes enabling the students to understand and "cultivate" new environmental, structural or material performances and behaviours. A third set of digital simulations is achieved by animating the digital diagrams and drawings in real time while time lapsing video techniques is used to capture spatial and behavioural effects of the prototype models as they unfold in time. Students invest efforts on developing different platforms to map dynamic information, being able to develop tools for visual integration of different data for simulation, articulation and evaluation of speculative ideas are key to the design process. In essence is about modelling self-organisation.

2.2. “GENERATION”

Studio #2: L-systems as a generative organisational method

The design methodology is based on using L-systems as a generative tool to conceive a design framework to promote the creation of stable, on-going relationships between organic and non-organic systems. This will allow the framework to operate in a sustainable way. The brief aim is to design a University campus in an abandoned industrial area. The main concept of the framework is that by using L-systems for re-writing conditions, the initial information or object is redefined by sets of rules as it grows.

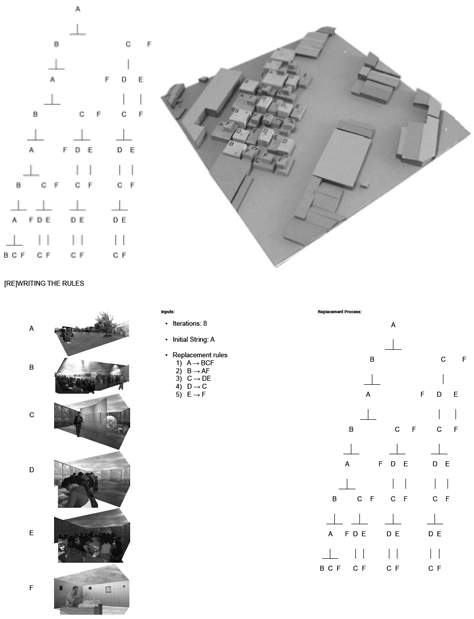

Figure 2. “Mutant Urban Device” Project, Year 4 Architecture (Dipl) Canterbury Architecture School 2009, UK.

The outcomes: a framework of spatial qualities (noise, light, thermal comfort, etc.) was mapped against functional requirements (studio spaces, library, dormitories, etc.) and an L-system framework was established to create a self-organisational system at an urban scale. Rather than layering discreet systems, the aspiration of the framework is to find points of flexibility and interaction in conditions, and determine how the dynamics of one set of spatial requirements can converge with other sets of spatial requirements flows to create not only improved combined fitness, but also unexpected qualita-

tive effects. The map then becomes the territory in the sense that continuities within the design process could translate into continuities into materiality.

2.3. "PERFORMANCE"

Studio #3: Parametric design in code

In this design studio the methodology proposed is to parametric design as a learning methodology, promoting the use of procedural techniques to help forge a closer connection between the process of form generation and the real, constructed design in one of two ways: either in how it is built or in how it performs. The focus of the studio is on creating systems for performance - driven architectural solutions using basic design computation and 3D parametric modelling technology. It represents a working method based more on procedure than geometric form which is a very different from traditional design thinking where the focus is on the representation of final form described geometrically. This can be easily fine-tuned and changed by the designer whereas in parametric design force a prior procedural representation in which the form is only the result of this designed procedure. When revising the model it is generally impossible to make changes at the level of final representation – form; it must be modified at the procedural level.

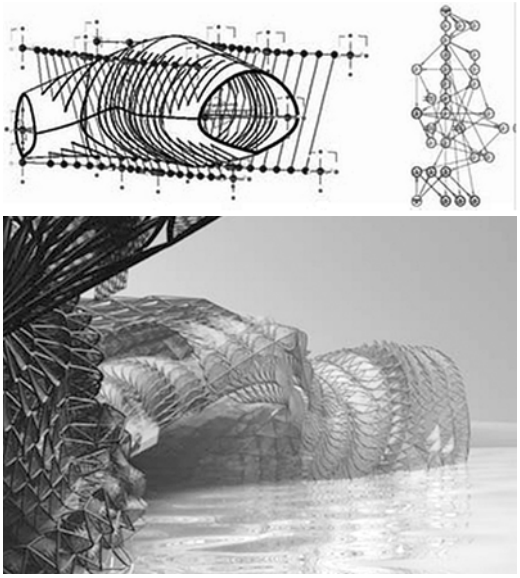

Figure 3. Parametric Design Stages, Workshop UCL, Bartlett ACC MSc 2008.

The outcomes: the projects methodologies are procedural rather than geometric, what is being designed is not the final form, but the steps taken to generate that form, and if these steps are closely grounded in the reality of the project, then the generative process actually forces the designer to consider the logic of design on a deeper level than the simple geometry and the drawing (Hanna and Turner 2006).

In one project for example (Figure 3) solar and mineral paths and other environmental factors of a salt water site serve as parameters to form a surface ideally suited for salt crystallisation on the edge of the Dead Sea. The result is a sweeping curve plane that responds to changes in the site and environment with a million of unique elements. Such a form as the model produces is well beyond the capacity of a human designer to realise through conventional drawing.

2.4. "BEHAVIOUR"

Studio #4: "Game of boundary" adaptive and reactive space

The brief is designed to be experiential through its connection of physical space, materials, exploration and celebration of intense effects of immateriality, and speculation about "smart materials". The aim of the brief is to open many directions for exploration where juxtapositions of material and immaterial and/or static and transient environments are investigated and co-exist. Additionally the students have to explore a theme via the construction of a full scale prototype.

The design methodology is based on cellular automata and the student's project presented here is called "Game of Boundary" inspired by the "Game of Life" cellular automata by John Conway. A translation into the physical world of the game was used to set up rules as a generative framework to explore how architectural elements could enter into a dialog with its inhabitants and surrounding environment.

The outcomes: In the project a 3D matrix of 9 pivotal elements rotate according to the proximity of users walking around the space. The proximity sensors trigger a set of rules to constantly rotate the pivotal elements in the 3D grid at random. The user that enters the grid space is subjected to the laws of the system to get through the maze. The spatial artefact is responsive to people's proximity, so it senses the environment. The project borrows its design logic from simple notions of ubiquitous electronic technology, artificial life, robotics, and human computer interaction (HCI) models as integral components of the design system.

Figure 4. "Game of Boundary" Hardware Set-up and final installation, High Technology, 3rd Year IAD, Canterbury Architecture School 2009, UK.

3. Discussion: algorithmic (process driven) concept versus contextual (narrative driven) concept

To understand this process-driven conceptual shift is the position in this paper. The working methodologies shown in the four studios require a great deal of explicitness and effort up front to create schemas, there are no possibilities to thereafter switch explicit, procedural representation of a form. The comparison of outcomes in the studios and the impact of digital approaches of the four studios is not the objective and it would be difficult to achieve mainly due to:

1. different cohorts in background and levels of education;
2. the briefs have different scopes, and scales of design and address very different design disciplinary definitions, often perceived as oppositions, such as sustainable development, versus ecologic urbanisation for example;

But what we can examine is that all studios use algorithmic [process driven] versus contextual [narrative driven] architecture, bottom-up tactical versus top-down strategic design. In each of the case studies the projects were developed by manipulating digital models and techniques that suited the theoretical and conceptual content of each project brief. In each brief a conceptualisation of 'digital material' and a unique digital model or digital technique appropriate to the material concept was employed. The studios explore processes that can organise a set of ideas and rules that can then modify the process by selecting alternative methods and techniques of exploration. They explore design methodologies based on a bottom-up process approach with very basic knowledge of computational tools. In fact in second studio, "Generation" - the L-systems approach is used in a totally analogue way. In all studios a very introductory level of knowledge is taught, also in all studios the work was developed in a short period of time – 2–5 weeks.

What these case studies show is that instead of asking students to define essentially formal representation criteria it asks them to define a set of variables of a design framework, then a computational definition can be utilised to facilitate a variety of solutions. It is a way of thinking that structures and relates tangible and intangible systems into a design proposal removed from digital tool specificity and establishes an holistic relationship between properties within a system. It asks students to start with the design parameters and not preconceived or predetermined design solutions. It is therefore the hope of this research to suggest that process-based methodologies can give assistance to designers to structure their own thoughts. But as with any design method of working, the set of tools used influences the designer's thinking. The fundamental difference is that all studios are fabricating and deploying tools of experimentation, by allowing students and tutors to understand and "cultivate" new environmental, structural or material performances and behaviours.

Acknowledgements

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AGGREGATES

Digital design for design 1

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Abstract. This paper discusses an educational design methodology for undergraduate studio instruction, which uses a systematic and research based design approach. Based on Lars Spuybroek's methodology that was originally developed as a one-year graduate and postgraduate studio, a new method for undergraduate teaching has been developed. The paper will discuss Spuybroek's methodology, as developed for the graduate and postgraduate program, and explain its adaption for undergraduate studio instruction. Spuybroek's approach is based on a model that starts with research in systems in general that is them tuned to a certain set of architectural questions and developed into parametric buildings in a stepwise procedure by delaying the specifics of site and program.

Keywords. Methodology of CAAD; education in CAAD; generative design; parametric modeling.

1. Introduction

Conventional architectural studios may start with research of site, program or a specific building technology that drives the design process, using digital tools as a means of representation. In recent years we witnessed a larger number of digital studios that have been taught with the emphasis on digital tools. Foregrounding the tool these investigations often focused on the investigation of formal novelties for architecture. Greg Lynn, Zaha Hadid and Patrick Schumacher are leading this method in the studios they taught in Europe as well as in the United States (Terzidis 2004).

The studio that will be discussed in this paper is an attempt to move the focus from the tool to methodology, as a constructive generic framework. The

discussed method is based on Lars Spuybroek's approach to teaching digital design, which he developed at Columbia University, University of Kassel and the Georgia Institute of Technology. Certainly, similar approaches to digital design can be observed at the Architectural Association in London, the University for Applied Sciences in Vienna, at MIT, at University of Pennsylvania and at other university. Instead of analysing the similarities and differences between the different programs this paper will specifically focus on Lars Spuybroek's approach to digital design.

2. Research and design

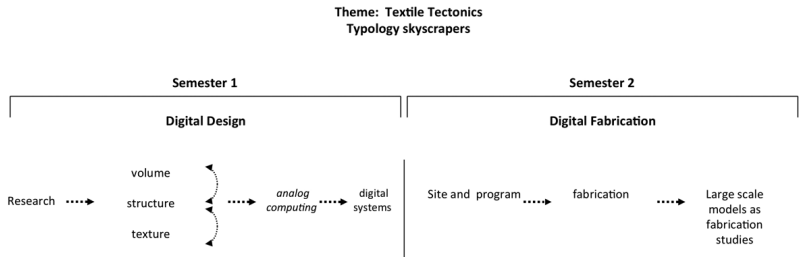

Figure 1. Structure Ventulett Studio, L. Spuybroek.

Lars Spuybroek describes a paradigm shift in architecture in the foreword of R&D in the following way: "Information was text; form was architecture. Today, things have changed. Tools aren't fixed anymore, type isn't fixed anymore, demographic maps have been changed completely, products are being replaced by half-products… and everything seems to be fluid and vague. Design requires more and more research, since the transfer into architecture is without prefixed codes, without prefixed forms and procedures. It is no longer enough that we do research before entering a design phase: we now have to research design itself." In that context he postulates that our methods of teaching and designing must become more rigorous and clear. His teaching method seems to follow that aim.

Lars Spuybroek's work at the Georgia Institute of Technology is the best documented of the three schools mentioned above due to the fact that the Ventulett program was published each year in the Research and Design series - R&D I and II. His teaching methodology is based on a two semester program with two subsequent design studios, two theory seminars and a symposium that is linked to the topic of the specific year (2007 Uniformity and Variation, 2008 Textile Tectonics, 2009 Seeing and Feeling, 2010 Digital Craft, 2011 Beauty). His program is open to students at the end of the graduate program

and postgraduate students. The first semester in his program deals with digital design and the second with digital fabrication.

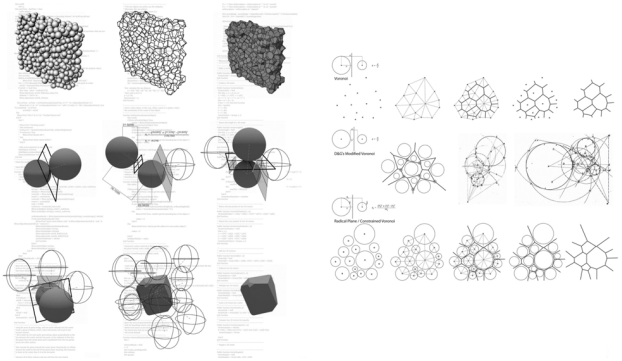

Figure 2. Foam Tower (R&D2). Instructors Lars Spuybroek, Daniel Baerlecken. Students: Geoffrey Braiman and Dave Beil.

The first semester starts with research in pattern systems. The studio Textile Tectonics in 2008 for example, published in R&D 2, focused on the structure of vertical building types. The topics researched in that studio include gothic figures, braiding, foam, radiolaria and minimal path systems based on Frei Otto's form finding experiments with wool threads (Kolodziejczyk 1992). For each topic students were asked to diagram patterns as systems with varying figures and their configurations. In this first phase these systems were understood by the students through analogue computing – Gaudi and Frei Otto – and through rigorous diagramming and subsequent translation into a digital systems. The diagrams were parametric and were still able to vary within a certain defined range. During this phase students worked in pairs, which helped to foster a dialog-based approach.

In a second phase these pattern systems informed architecture in one or more of 3 interconnected systems: a façade system (structural and/or ornamental), a structural system and/or a volume/massing system. A pattern for instance might have been first used to inform a structural system that further informed the distribution of program elements, the positioning of floor slabs, the composition of the façade, the formation of apertures and possible relationships to a specific site. Students in such an approach are also challenged to develop a wide range of prototypes for building components and elements and their possible relationship. Tectonic systems are developed to potentially respond to different external and internal forces such as site and program without being tailored to a specific context.

In the second semester students are using their systems to respond to parametric forces of a specific site and program. The projects actualise themselves in this process as a consequence.

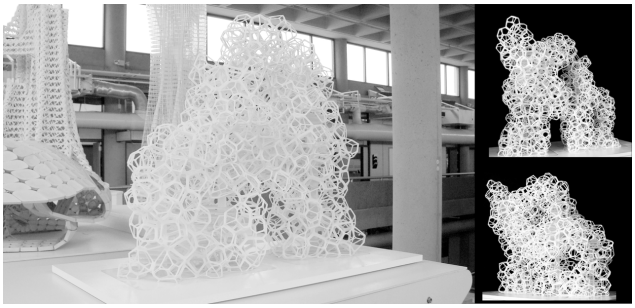

Figure 3. Spuybroek's Borgesian "zoo": Foam Tower (R&D2), students: Geoffrey Braiman and Dave Beil; Instructors: Lars Spuybroek, Daniel Baerlecken.

The second semester focused further on the exploration of tectonic properties through digital fabrication with an aim to produce "large models, all involving computer numeric control, which would eventually add up to a potentially infinite Borgesian "zoo", a Wunderkammer of variations and studies… (Spuybroek 2009, p. 7)." These models included 2 m high structures as well as mock-ups in full-scale façade structures.

3. Studio methodology for Design 1

In summer 2011 Lars Spuybroek and we were asked to develop a new teaching method with the second year undergraduate studio. This studio is the first design studio in the undergraduate architecture curriculum at Georgia Institute of Technology. After a Common First Year, Design 1 is the first design studio, in which students are asked to develop a larger architectural project. Students are also new to digital modeling, fabrication and scripting.

Different to Lars Spuybroek's option studio that is usually co-taught with about 15 students we had 60 students, split in 4 groups of 15 students each. In order to maximise the consistency in approach, structure and outcome the studio was structured into four parts with a midterm review positioned halfway in the process. The four parts were titled: 1) Aggregation Techniques: Analysis, 2) Aggregation Techniques: Digital diagramming, 3) Differentiation and Integration: Programming and Siting the Aggregation, 4) New skills: Drawing, modeling and rendering.

Beside the challenge of compressing a studio that Lars Spuybroek usually teaches over a period or two semesters into one semester the main challenge

was to transform an upper level option studio into a beginning design core studio. This change raised three main questions: First: How do we respond to the core curriculum agenda and cover aspects such as program and program site relationships, second: How do we connect the introduction of architectural representation convention of with the studio's overall agenda and third: How do we integrate the teaching of software with the studio.

These three challenges are not so much an issue in upper level option studios, where it can be assumed that students already have the right software skills, are familiar with architectural representation techniques and have already exercised architectural problems that deal with a certain complexity of program and site. On one hand the challenge was to introduce a large volume of material to the students simultaneously within a very short time frame. On the other hand the parallel introduction of software, representation techniques and complex architectural issues opened the opportunity to redevelop the way digital tools are introduced in the undergraduate curriculum.

In the previous schools curriculum software courses were taught separately from design studios and framed around different applications. In many cases these tools informed renderings of final projects, but not the design process itself. In this studio we focused on building digital skills more integral to an architectural design process. Rather than introducing technical knowledge separate from design, digital skills are introduced to become the instrument for design. Talking about digital skills does therefore not mean the tool itself, but the method that drives design. The techniques and tools of design are linked to the design through method. Similar to this analogy students in our studio were asked to develop methods, digital methods in our case, before introducing an architectural program and a site. Our goal was to walk students through a process were "digital" methods are used to define internal relations within the program and relations between the program and the site.

4. Structure

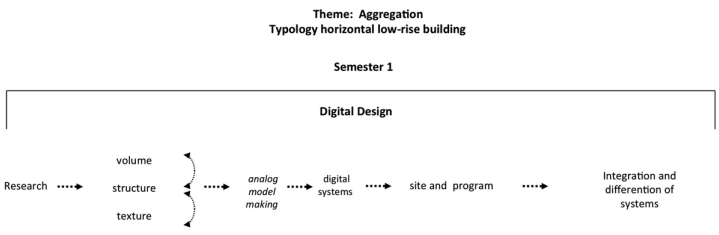

Figure 4. Structure undergraduate studio aggregates.

The studio that was first taught in the Fall semester of 2011. An investigation and unpacking of existing non-architectural systems was used to develop digital methods, which were used to develop an architectural project at a specific site. Students were asked to diagram and unpack aggregates as rule based systems, collections of items that are gathered together to form a total quantity. (Middle English aggregat, from Latin aggregatus, past participle of aggregare to add to, from ad- + greg-, grex flock, join together, attach) Climate for example is the aggregation of all local weather formations over longer periods of a season or year – with its local variations.

4.1. AGGREGATION TECHNIQUES: ANALYSIS (WEEK 1–2)

The studio did not investigate a material aggregate as a construction material (Dierichs and Menges 2010), but as a system or architecture embedded within aggregational systems, that can be used to inform texture, structure, volume, program and any other architectural system. The aggregational parts are understood as varying parts, parametric parts with flexible properties that respond to different vectors or forces within their systemacy. This method followed an evolutionary process, which allowed for differentiation and integration of different systems with increasing complexity: "Complexity increases when the variety and dependency of parts increases. The process of increasing variety is called differentiation and the process of increasing the number or strength of connections is called integration. Biological and cultural evolution produce both differentiation and integration at many scales and levels… (Weinstock 2010, p. 30)." This development of architectural complexity through differentiation and integration was developed in successive order in different layers and scales and not all at the same.

The types of aggregations researched were: cracking and nesting of different floating sea ice types such as drift ice or pancake ice, aggregation of people in a park, patchwork in self-organised African markets, complete and incomplete states of mud cracking, radial and linear types of glass cracking, diffuse-porous and ring-porous hardwoods, log driving, slime mold, igneous rocks, metal alloys, flocking of herds such as sheep, patterns of angelfish, sand formations and crocodile skin. For the first five weeks the students worked in pairs and choose an aggregational structure from the given list of topics. Students learned how to transform images into diagrams in order to explain and gather a fundamental understanding about their aggregational system. The tools used were Photoshop, Illustrator and Rhinoceros. Students were asked to trace the images with typical diagram tools such as lines, dashed and dotted lines, arrows, colors and texts in different sizes in order to learn how to represent their analysis as a set of rules and pseudo-scripts.

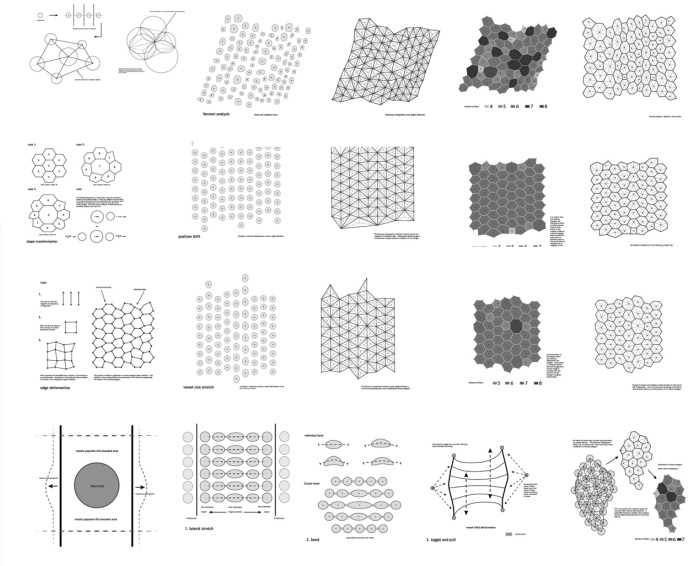

Figure 5. Analysis of ring-porous and diffuse-porous wood.

4.2. AGGREGATION TECHNIQUES: DIGITAL DIAGRAMMING (WEEK 3–5)

In this phase students transformed the analysed material into more architectural issues using specific architectural software applications such as Rhinoceros. They started by re-working the analytical diagrams into 2D patterns first and later into 3D patterns and morphologies. At the end of this phase the students had a broad range of aggregational structures, forms or patterns with parametric variation. This work was explored through large fields/carpets of configuring parts illustrating the variability of these parts and the rules of configuration. At this point parametric history editors with real time feedback were introduced to explore variability.

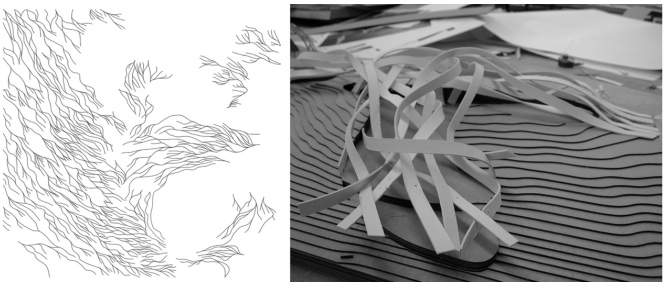

Figure 6. 3d system based on a 2d system of herds movements.

4.3. DIFFERENTIATION AND INTEGRATION: PROGRAMMING AND SITING THE AGGREGATION (WEEK 6–10)

The teams split up in this phase and the students worked individually from this point. They were asked to explore how aggregated systems can respond to the typology of the architectural program and to the site. The program for this particular studio was a cultural center with exhibition areas, a multipurpose area, a small indoor-theater, an outdoor-theater, a cafeteria, administration areas and back of house facilities. The students could suggest additions to the program in order to accommodate for site or program specifics. The site, a larger area in a local park suggested a multitude of local qualities and potentials resulting from topography, vegetation, vistas, accessibility and the existing program within the park. The site was selected intentionally as an anti-urban setting to better respond to the student's selected aggregation types which all operated on a surface through horizontal extension. The students needed to select a specific site within a larger site area. They were further asked to develop a rationale and narrative for that choice through diagramming techniques.

The design process in this phase comprised the development of the related sub-systems of program, circulation and navigation. Each of these categories is developed in accordance with a specific spatial logic of the aggregation and a sophisticated spatial distribution of the program domains. Boundary conditions between program parts had to be studied to integrate or unify the different domains. A system of navigation and circulation was developed as a mean of orientation through the aggregational structure, which is especially challenging for non-hierarchical structures.

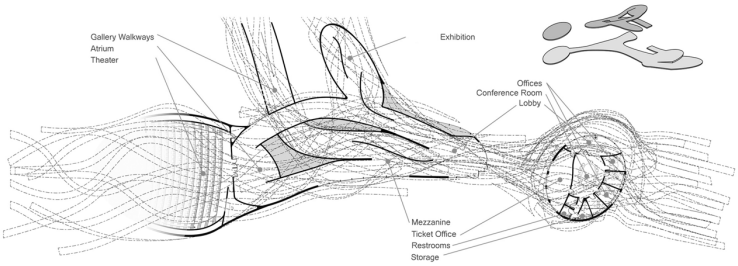

Figure 7. Plan developed from a 3d systemic model.

The students used diagramming techniques closely linked to the diagramming techniques developed in the research phase to adapt the aggregational systems to the requirements of program and site. For example programmatic bubble diagrams, which reflect social relations and hierarchies transform into spatial or tectonic systems, which followed the systemacy as previously devel-

oped in the research phase. Site diagramming involved traffic flows, sight lines, sun and shadow behavior, but also experiential factors such as light or sound which now become part of the aggregational system.

The analytical research that first let to diagrams has now become a potential start of a project, which allows to further-develop ideas for stairs, entries, apertures etc. as part of the systemacy. In this phase the students learn additional modeling techniques in Rhinoceros, extracting digital information from the 3d file for physical model making, 2d drawing with AutoCAD and additional techniques in Grasshopper. A strong emphasis lied on the bi-directional feedback between digital model and physical to question both realms.

4.4. NEW SKILLS: DRAWING, MODELING AND RENDERING (WEEK 11–16)

In the final phase the studio focused on production for the final presentation that included drawings, renderings, diagrams as well as physical and digital 3D models.

5. Discussion

It is, of course, difficult to quantify improvements in architectural design, but it can be observed that the student's skills in drawing and digital representation show a deeper understanding of space and structure and that the methodology has fostered a conceptual understanding of tools and techniques within a design process.

During the midterm review and the final review external reviewers commented on the methodology of the studio. Most comments were concerned with the scope and complexity of the project. One group of critics was recommending a more research driven agenda without any site or program, whereas the second group criticised the lack of a deeper understanding of the site and program. Both positions have merit, but the lightness of site and program was intentionally selected for the second year students: Students in the second year and first year in architecture after the Common First Year are generally longing to design their first building, but needed the guidance of the research phase to be able to develop a scheme.

From the student's point of view the studio was a large success. Also one constructive critique in the evaluations of the course was that the methodology came per surprise. We are therefore planning to offer more theoretical background or more lectures that would situate this methodology in a larger context if thought for second time.

Acknowledgements

Figure 2 and 3 show the foam tower by G. Braiman and D. Beil (instructors L. Spuybroek and D. Baerlecken), figure 5 shows diagrams by O. Taylor and A. Wang (coordinators: L. Spuybroek, D. Baerlecken and instructor: J. Stanford), figure 6 and 7 present the work of L. Kvasnicka (coordinators: L. Spuybroek, G.Riether and instructor: A. Vialard).

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7A ANIMATION AND VIRTUALISATION

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DIGITAL MANGA VIRTUAL ENVIRONMENT

Bi-tonal visualisation for texture-mapped virtual environments

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Abstract. Bi-tonal and non-photorealistic architectural depictions can be employed to develop a narrative that engages the reader with not only the visual aspects, but also aspects of the storyline. Architecture is subsequently not only represented through its factual dimensions of length, width and height, but is extended to intangible realms. This paper presents a modified rendering appearance of the graphical depiction of a Virtual Environments (VE) -software to communicate design akin to Japanese cartoon (manga) depictions whereby we expand the two-dimensional manga-images into a three-dimensional VE. The modified visualization can be used for storytelling and developing a narrative that professionals and laypersons alike easily can access, understand and interact. The bi-tonal depictions offer users to experience both, visual richness of the original model, as well as enhanced design communications.

Keywords. Digital manga; virtual environments; architectural depiction; visual communication.

1. Introduction

Digitally generated, bi-tonal, non-photorealistic depictions are increasingly becoming popular around the world because of its distinct graphical quality with its elegant use of rich set of screens, tidy and fine drawing styles of a black and white (b/w) drawings, and its engaging way of storytelling. This method of visual communication provides another realm for representing drawings, photography, or architectural design being real or virtual. Although conventional architectural drafting depend on pure b/w patterns and lines, or is in other words bi-tonal represented, they lack of personal engagement and

legibility by non-professionals. In a sketch however, it is possible to perceive the variety of textures and lines as elements of a building or details such as materials or surface textures by using this non-photorealistic rendering style. For example, in popular Japanese comics –manga– the artists lay multifarious screens to express different semantics. Hatches are selected not solely according to the shading, or tone, but also according to texture, material property, chromaticity or even function of the underlying design or architecture that is being depicted and expressed.

The graphical depiction of three-dimensional Virtual Environments (VE) mostly presents the user with a more or less photo-realistic chromatic depiction of its scenes. These depictions lack of the artistic qualities of sketches and often have a dry and sterile *look and feel* of their interface (see Figures 3 and 5). In this paper, we present a novel method how a bi-tonal non-photorealistic rendering can be used to develop narratives akin to manga in order to experience both, visual richness of the original architectural model, as well as enhanced design communications and engagement of the storyline.

2. Digital bi-tonal architectural depiction

Architectural drawings and sketches are a universal convention that uses symbols, screens, hatches, line-types, -styles and -widths to describe (elements of) a design, its properties, functions or materials (Figure 1). They are filled with represented knowledge and key information for a specific composition. In addition to that, architectural drawings are flexible and allow the creativity of individual architects to influence the overall style of the screens and impression of the design. In contrast to this, Computer Aided Architectural Drafting (CAAD) typically has no personal style and depicts neutrally norms of the architectural, engineering and construction (AEC) industries (Figure 2). Gross's (1996) development of an *Electronic Cocktail Napkin* identified the need to create digital drawings that can be ambiguous and imprecise; yet they have to be precise enough that they can be computed and identified.

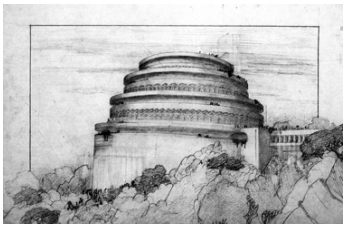

Figure 1. Gordon Strong Automobile Objective and Planetarium; sketch by Frank Lloyd Wright.

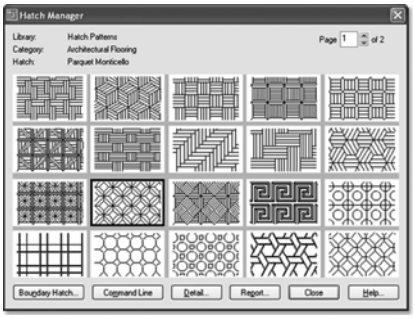

Figure 2. Hatch Manager, Screenshot of Autodesk AutoCAD.

A straightforward way to produce computational bi-tonal images from grey-scale/colour photographs is halftoning. It exploits the spatial integration of human vision to approximate the intensity over a small local region with only b/w pixels (Floyd and Steinberg 1974, Jarvis et al. 1976, Knuth 1987, Ulichney 1987).

Another technique is hatching to produce bi-tonal images. Winkenbach et al. (1994) generated pen-and-ink illustrations by rendering a geometric scene with prioritized stroke textures.

Images generated by halftoning and hatching, containing more or less uniform patterns that may appear monotonous to the reader; conventional manga instead uses a wide variety of screens to enrich the viewing experience. Qu et al. (2008) describes in detail the technical aspects of their computational manga screening tool that utilizes the variety of pattern to preserve the chromaticity distinguishability as well as the tone and texture similarities. Based on their work, we proposed to develop their system to generate manga style architectural drawings including screening, line drawings, and the final rendering (Schnabel and Qu 2011).

Goldschmidt (1991) argues that the architectural sketch is a mode of visual thinking and communication, which is crucial to a conceptual framework of the depicted architectural design. Despite the advancement of digital media, there remains a certain quality of a hand drawing and therefore the architectural sketch remains an important medium of designing, communicating and construing. It incorporates abstraction, fuzziness as well as clarity and sharpness. As that, the expressions of lines and hatches themselves become the objects of meaning and interpretation, a sketch explores from overall relationships to fine resolution of detailed attributes of the depicted design. In order to make the communication of space more precise the drawing makes use of graphic modifiers to convey information that go beyond the pure outlines or

dimensions of the spatial arrangement (Robbins 1994), which are also the underlying principles of manga drawings.

3. Visualization in virtual environments

With the advent of VE, they are extensively used to visualize, simulate and communicate architectural and urban scenarios. El Araby and Okiel (2003) state that "the importance of environmental simulation is being crucial for almost all environmental design professions for presenting simulations of reality to the observer to predict his responses of the real situation." In this context, according to McKechnie (1977), simulation techniques are critical to decision-making processes of designers as well as their communication of their design proposals. Yet, conventional depiction techniques were often criticized as they lack some important features that affect their reliability in depicting the real environment, such as the depth of visual field and passive interactivity, while at the same time VE lack on artistic expressions that appeal to a wider spectrum as sketches would do. Subsequently our research aims to intersect sketching with VE to address some of these issues and develop a novel realm and visual communication.

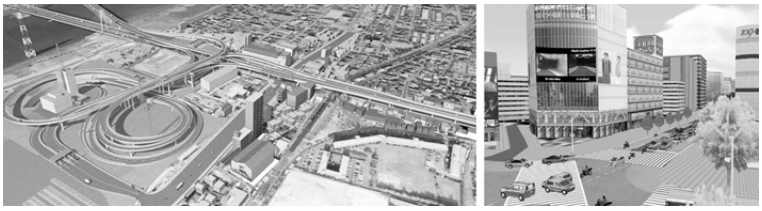

Figure 3. Screenshot of UC-Win/Road: Phoenix, AR (left) and Shibuya, Japan (right).

For our research, we chose a typical VE software - *UC-Win/Road* {http://www.forum8.co.jp/english/uc-win/ucwin-road-e1.htm} by *forum8* {http://www.forum8.com} - that is used for interactive virtual reality modelling and simulation for construction, planning, designing and visualisation (Figure 3). It is a tool for project visualizati on and consensus building for almost any type of urban project. The software is also used extensively to present and communicate design proposals to laypersons and to visualize simulations and various planning scenarios. The *look and feel* however, is akin to typical many VEs: technical and quasi realistic. This representation deemed to us as ideal test environment to explore the impact and the resulting possibilities bi-tonal non-photorealistic visualization. Akin to Brown (2001), these visualizations are generated to be different from reality and aid critical design discussions.

Hereby the visualization acts as mediator and visual clues in the storytelling of design and planning proposals. The software relies on 2D textures that are mapped onto geometries of objects and 3D models. In order to change the visual appearance of the model, we will replace the original textures with 'mangarized' ones.

4. Digital manga virtual environment

Based on the work by Qu et al. (2008), we developed further their *manga-me* software {http://mangatech.tk} to automatically generate texture maps for the VE of a digital urban setting of any (UC-win/Road-) model. Richness preserving manga screening offers a solution to generating bi-tonal non-photorealistic screening for an input colour image. The goal is to preserve the visual richness in the original texture map of the model by utilizing not only screen density, but also the variety of screen patterns. Our system consists of two major components, screening and line drawing, which are similar to the conventional manga production. For the line drawing part, we used a line importance model to rank each line. With this ranking, we can control the detail level of lines needed in the particular texture map for of the given UC-win/Road model, via a simple threshold. For the screening process, we utilize the technical solution of Qu et al. (2008) that automatically selects appropriate bi-tonal screens to represent (or fill up) different regions in the image.

Each type of screen supports a range of densities to represent different intensity. Therefore, whenever a screen is selected for a region, the intensity of this region can be approximated by matching the screen density. The major difficulty is to select an appropriate type of screen for each region, which can preserve the texture similarity and the colour distinguishability of the target regions in order to preserve the architectural content. However, to simplify the process we used only four to six different screens. This enabled us to archive results faster and have an overall more coherent texture maps that assemble the model of the VE. Akin to the generation of a 2D manga image as described at Schnabel and Qu (2011), our system starts by loading a texture map of a given model and segmenting the map into regions (Figure 4a). Then, the system provides the optimal assignment of screens for different regions (Figure 4b). This is done by first, projecting the available patterns from high-dimensional texture feature space to the low dimensional colour space, and then optimizing texture similarity (Figure 4c). In addition, we are still able to control and/or override the selection of screens via simply tuning a few parameters. Finally, lines are detected and overlaid on the screens to finish the result and the original texture-map file is overwritten. The process has to be repeated for each texture map of the given model.

Figure 4. (a) An image with rich content will have thousands of segments. (b) Semi-automatic segmentation plus manual screen assignment. (c) Our automatic screen assignment significantly relieves user intervention producing reasonable results.

5. 3D digital manga implementation

We successfully converted ca. 2,500 texture maps of a sample model. Each texture map of the original model was mangarized individually without any context information of adjacent maps and then loaded back to the VE model. Some results can be seen below in Figure 5.

Figure 5. Screenshots of UC-win/Road VE: original (above) and manga version (below).

In September 2011, this novel '3D digital manga' was showcased at the *Tokyo Game Show* (TGS) {http://tgs.cesa.or.jp} to test the acceptance and engagement with the general public. Two versions of the same model were presented on a large high-definition screen of ca. 3.5 m * 1.5 m. Using a mock-up car, users could 'drive' through an urban VE using either the mangarized or the original visualization (Figure 6). An online movie-clip of the digital manga VE, titled 'World16: Manga-Style VR Environments' (2011), can be found at *YouTube* {http://youtu.be/GmN_HJGYfBU}.

Figure 6. Immersive experiences at TGS: Manga VE (left) and original VE (right).

An interview with participants of a focus group stated that due to the interactivity, animation of the VE model and the augmentation of driving sounds they could experience a strong 3D immersion into the VE model. They affirmed that compared to the 'normal' version the 3D manga VE allowed them to understand better the design intent and fostered their spatial understanding of overall urban scenario. It was easier for participants to focus on certain aspects of the urban design and their experience by moving (driving) through the VE since the bi-tonal version allowed more engagement and had less visual noise. Participants confirmed that the quasi-realistic version of the original visualization was often distracting due to its constant break of visual quality of texture-maps, perspectives, etc. and its inconsistency of lights and shadows. Despite some of these issues were also found in the manga visualization, due to the overall look and feel of the model these errors became factors that enhanced the users' experiences and allowed for a stronger emotional stimulation.

Since the VE software maps the individual textures onto 3D primitives to achieve their spatial visualisation, some of the mangarized maps did not match without any error onto the clear-cut original shapes and inconsistencies or errors arise. The biggest problem occurred due to the effect that the manga-me software is optimized to transfer images that contain context and diverse image components, information, multiple colours, textures, etc. Most of the texture maps of the VE-model however, were monotone, containing just one single texture, colour or hatching that referred to a specific spot of the 3D model. Subsequently the mangarization of some maps were not as good as they would be in a 2D image that is full of context information. Some of these textures had to be adjusted and improved later. The software needs some further development to fit for all purposes of architectural visualisations in 2D or 3D. Despite this, the resulting visualization of the mangarized models presents a distinct drawing style and allows for a unique experience and immersion of the digital manga VE.

Figure 7. Storytelling by including visitors into a mangarized urban scene

Figure 8. Top: Digital Manga Sample at TKS
Bottom: Screenshots of UC-win/Road VE

5. Conclusion

Our novel '3D digital manga' allows designers develop a narrative that is akin to comic and cartoon reaching out for a wider audience for design communi-

cation. The bi-tonal non-photorealistic depiction of VEs improves the users' immersion, stimulation and engagement with the depicted architectural design in its urban setting and its visual simulation. Despite some limitations of the software, we demonstrated successfully how our manga visualization for texture mapped 3D VEs allows designers to communicate both, visual richness as well as aspects of a narrative. Hereby architectural design communication is extended to a genre that is not only popular and commonly accepted, but also carries rich and meaningful content that merges sketching and digital drafting. Our technique allows for that architectural or urban design is communicated beyond the graphical depiction of architecture itself by elevating it from the backdrop to the protagonist of a mangarized narration.

Akin to Calderon et al. (2006) and Ng et al. (2006), we plan in our future research to address cinematic aspects of our architectural digital manga visualizations and generate animation techniques allowing designers to create architectural animations based on bi-tonal non-photorealistic depictions with the same ease as conventional animation methods. The challenges hereby are to adapt and consider solutions for the 'depth of cinematic illusion' and other relevant cinematic aspects that can be considered in a VE and to identify appropriate stages for such visualisations and design communications in architectural practices.

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The authors wish to acknowledge the research that lead to the development of the software 'manga-me' {http://manga-me.tk} by TT Wong, PA Heng and Y Qu., CUHK. A free version is available as an *iPhone-App.* We are grateful for the great expertise and advice that members of the *World16*-Group {http://world16.forum8az.com} offered during the development of this project as well as Mr Ito, President of forum8, for his generous support.

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MOVING IN FILMIC SPACES

Relating camera movements to spatial archetypes in architectural animations

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Abstract. Architects sometimes use architectural animations to explain their designs. To probe the practice of architectural film/animation, this paper assembles filmic spaces as a conceptual tool that connects spatial archetypes with camera movements.

Keywords. Architecture; animation; representation; film; camera.

1. Introduction

Architectural animations are often shaped by CAD software, which depends on the creation of paths, offering various degrees of freedom, little guidance, and few editing options. This leads to conventions of depicting movement in space through devices such as fly-throughs, combined with quickly changing angles, rotations and swirls that tour the building, speeding up at times and slowing at others. Techniques from cinema can yield richer spatial experience.

This research examines spaces in architectural animations in terms of both form and camera movement, encompassed by the term "*filmic spaces*". In order to achieve this goal, we present a study in two stages. In the first stage, we review relevant literature on architectural animation that ties different types of "spatial forms" to various "camera movements". We develop a "*filmic space"* concept based on Cullen's *serial vision* (Cullen 1995), who views spatial experience as a transformation of form revealed through movement in space. We then discuss the outcome: *filmic spaces*.

Instead of regarding space as a static form, we view space as one that changes from one state to another through camera movements. To understand the relationship between spatial forms and camera movements, the second stage comprises a close-reading analysis of films, which looks for filmic spaces, and understands how spaces and camera movements are related.

2. Literature review

The design of an architectural animation is strongly tied to the intended goal. These can include non-commercial goals, such as exploring design alternatives and decisions, or documenting a historic building. Commercial goals can address data-communication, educating and informing about the building form, design features, and construction methods in order to promote design to clients and developers. Animations are also used to make an impression and convey an experience to occupants who are being sold a dream or lifestyle (Rafi 1998, Serrato-Combe 2004, Koutamanis 2005, Sanguinetti 2005, Kwee et al. 2006, Swathika et al. 2006, Alvarado 2008).

Architectural animation design is also influenced by the audience. For instance, if the audience were developers of large-scale projects, the animation will tend to have bird-eye views and fly-throughs to demonstrate the overall design. Meanwhile, when the animation addresses potential occupants, the aim is often to sell them an experience or a life style, and we would find more low-angles and immersed points of view. But if we were to move beyond these general impressions on architectural animations, how does previous research address the issue of architectural animation design?

Many previous studies on architectural animations relate camera movement to space types (Goldman and Zdepski 1987, Goldman and Zdepski 1988, Kwon and Nagakura 2004, Alvarado et al. 2005, Chatzitsakyris and Nagakura 2005, Calderon et al. 2006, Alvarado 2008). Since spatial form can become overwhelmingly complex, they start by identifying simple forms like: linear, layered, bent, broad, and tall spaces (Kwon and Nagakura 2004); arena, and maze (Nitsche 2008); path, edge, district, node, and landmark (Lynch 1960); composition, rhythm, scale, proportion and verticality (Calderon et al. 2006). Following the tradition of previous literature, we turn to film to perform close-reading analysis. This is to understand the nature of filmic spaces as a combination of camera movement and spatial form.

3. Close reading films

Close-reading required the careful study, analysis and interpretation of the particulars in a film. Through disciplined immersion, the perceptive senses are

attuned to observe and extract repeated patterns (Kain 1998, Mantex 2011). We selected film clips with strong architectural components and spatial features, and those featuring spatial exploration. We searched for spatial archetypes and noted their connections to certain camera movements. We stopped encoding when we have reached saturation, a state when no more can be learnt from additional viewing. These films include: a scene from *Marie Antoinette* (Coppola 2006) in which Antoinette explores Versailles for the first time, a chase scene in *Brazil* (Gilliam 1985), in which Sam runs through a series of narrow arcade spaces and ends in a funeral home; a scene from *The Glass house* (Sackheim 2001), in which two teenagers explore the extraordinary home of their caregivers; a scene from *Running Scared* (Kramer 2006), in which an abducted child searches the apartment of his kidnappers for an exit; A scene from *Duplex* (DeVito 2003), where a young couple explore a duplex house before deciding to buy it; the Spectra Town scene from *Big fish* (Burton 2003); several scenes from *The Fall* (Singh 2006), which show monumental buildings; scenes from *Gladiator* (Scott 2000), including when the city of Rome is shown through a bird-eye view, and when the gladiators are awed by the monumental scale of the coliseum.

The outcome of our analysis combines camera movements, spatial types and characters into what we call *filmic spaces.* We argue that such triples provide elements with which to conceive and develop architectural animations.

4. Filmic spaces

Filmic spaces associate spatial forms with specific camera movements. We start with simplicity before moving on to complexity, and thus identify basic camera movements corresponding to three primary shapes: (1) Point, comprising a stationary camera position in space, observing occurring actions, but not affected by them; (2) Line, where a camera travels along a path from one point to another. Lines comprise dolly forward or backward, pedestal up or down, and tracking-sideways left or right; (3) Circle, where a camera rotates around a central point. Primitive motions for circles include a pan (left/ right outward-rotation), an arc (inward-rotation), or a tilt (upwards or downward-rotation, Figure 1). We then proceed to the application of these basic camera movements to convey spatial archetypes. These basic camera movements can either reinforce *explicit* spaces, or create *implicit* spaces: ones that are not physically defined. In the following sections, we demonstrate several filmic spaces, with references to key films in which they occur. We give each filmic space a title in the form of CAMERA:SPACE:CHARACTER, describing respectively the camera movement, space type depicted and role of character. When a character is not involved, the last element of the triple is null.

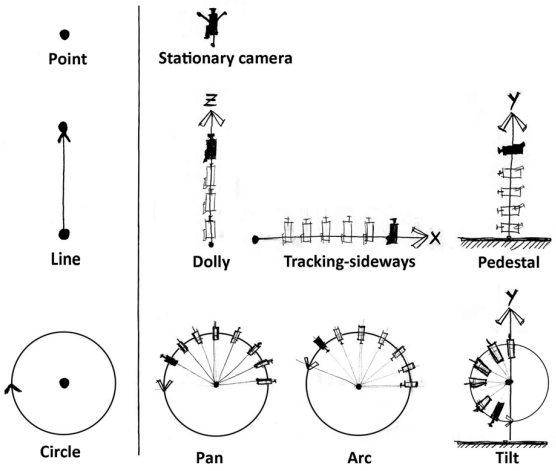

Figure 1. Basic camera movements include point, line and circle.

4.1. POINT:AXIS:COUNTERPOINT

A stationary camera observes characters moving against a spatial background. The characters amplify spatial qualities. In Marie Antoinette, POINT:AXIS:COUNTERPOINT is used to convey a major axis at Versailles and to convey the vastness of space in with respect to human scale (Figure 2).

Figure 2. A stationary camera observes characters moving across the screen, revealing space in this scene from Marie Antoinette (Coppola, 2006).

4.2. LINE:PATH:FOCUS

One of the horizontal camera movements is the dolly, which penetrates the depth of space. In this pattern, a dolly movement aligns with the passage of

a character through the space. The movement may observe the character as a third person or as a first person. The character serves to reveal the path and to give meaning to its traversal. Examples of such paths include a road defined by floorings and ceiling (Figure 3a), or an arcade defined by vertical elements on the edges of a path, creating punctuation between solid and void (Figure 3b). A path can also transform from one state to another. For instance, in Figure 3c, a clearance turns from narrow to wide, dark to bright, and inside to outside, giving a feeling of relief. The tunnel gives the reverse effect. Another horizontal camera movement is Figure 3d, tracking-sideways, which emphasizes the width of space. It tracks subjects through silhouetted foreground elements to establish the context in which they are situated, or reveal the perspective depth of space. In Figure 3e, a combination of tracking-sideways and dolly movements help create a reveal effect, by having a visual surprise concealed behind the gate, then revealing it through camera movement.

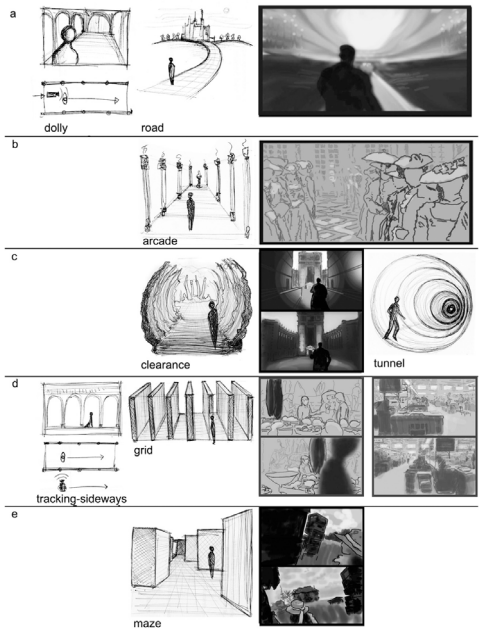

Figure 3. The linear camera movements, such as dolly and tracking sideways, emphasize spaces such as path, arcade, clearance, tunnel, grid and maze.

Figure 3 reveals these linear camera movements. The dolly movement is used for spaces like a road (Figure 3a), or an arcade (Figure 3b) created by people standing on the edges of the path in a scene from *Marie Antoinette* (Coppola

2006). In Figure 3c, a tunnel and clearance space is created in a scene from *Brazil* (Gilliam 1985). In Figure 3d, the tracking-sideways movement reveals the market place where the characters walk in a scene from *A Series of Unfortunate Events* (Silberling 2004), and also reveals the depth of the grid space in a scene from *Manufactured Landscapes* (Baichwal 2006). In figure 3e a combination of dolly and tracking-sideways camera movement follows the protagonist to reveal a visual surprise behind the gate in a scene from *Tideland* (Gilliam 2005), creating a maze-like space.

4.4. LINE:VERTICAL SPACE:NULL

Tall spaces profoundly affect architectural experience. The standard horizontal orientation of moving images is ill-suited to convey such experience. Filmmakers use camera movement to convey verticality. Such movements can also create implicit space that is experientially more than physically defined. For example, the boundary between a village and its surround may define a gate. Such implicit spaces may mark the threshold between two territories, or serve simply to introduce or exit a scene. Characters in this pattern play a lesser role or may even be absent – the focus is on conveying spatial effect.

Figure 4 reveals the vertical camera movement can emphasize the length of a shaft space (c), through (a) a tilt, as in *Marie Antoinette* (Coppola 2006), or (b) pedestal movement, as in *Pan's Labyrinth* (Del Toro 2006). In (d), a scene from *A series of Unfortunate Events* (Silberling 2004) implies a gate space, as the camera pedestals up when a character exits the space.

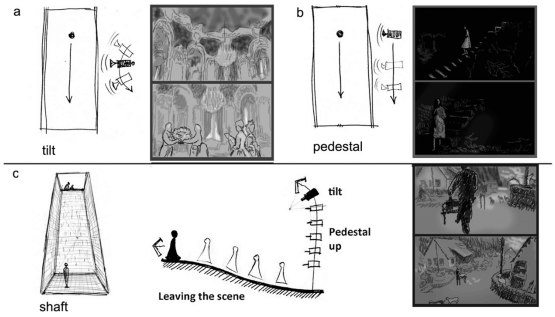

Figure 4. The vertical camera movements emphasize the height of space.

4.3. CIRCLE:ROTUNDA:NULL

A rotunda space can be evoked by a rounded camera movement, such as an arc in or a pan movement. The court space evokes various rounded camera movement like arc or pan.

Figure 5 reveals (a) The rounded movement enforces the feel of the rotunda, and includes movements such as (b) arc, observed in *The Fall* (Singh 2006) or (c) pan, in *Marie Antoinette* (Coppola 2006).

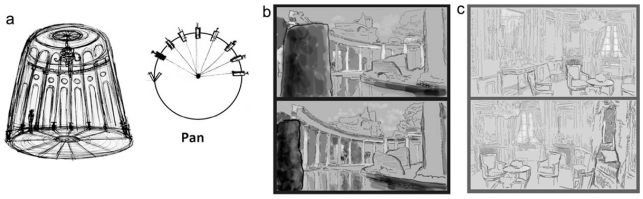

Figure 5. Rounded camera movements create a rotunda space.

6. Discussion and future work

This is a descriptive work that acts an introduction to the larger scope of our research. In this paper, we proposed the concept of *filmic spaces* in architectural animations. The proposed filmic space model combines spatial form with camera movement. Due to the limitation of this short paper, we have only explored two aspects, though they are not exhaustive. Our larger framework explores further cinematic techniques like narrative, editing, composition, lighting, sound, and camera angles.

Note

We used hand drawings for the figures in this paper for two reasons. First, copyright clearance for film segments can be difficult, while the copyright to hand-drawings lies with their creator. Using hand drawings means that we were unconstrained in sampling films and thus avoided any bias due to arbitrary difficulties in sourcing material. Second, hand drawing allowed us to emphasize drawing features to relate to points being made.

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ARCHITECTS ON ARCHITECTURAL FILM AND ANIMATION

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Abstract. As part of our inquiry about the practice of architectural film and animation and where it might go, this paper presents the results of interviews with architects on space, and on animation. We present their rich sense of space, and explain how they structure architectural film and animation. We found that architects wish to convey the subjective impact of design, but don't know how to connect film editing techniques to architectural ends. Computational design could fill this gap with, for example, drag-and-drop editing patterns.

Keywords. Architectural film and animation; concepts of architectural space.

1. Introduction

"Architecture is frozen music" — JW von Goethe. Movement through and around architecture plays the music. Architects use moving images to document, and to communicate data and experience. Not only do moving images include moving objects and flythrough animations, they also include sequential still images (drawings, renderings, photographs). Use of moving and sequential images is part of architectural practice. On one hand, architects have a rich sense of space, but they vary widely in their sophistication with respect to the craft of architectural film and animation. On the other hand, filmmakers and animators bring the sensibilities of their own profession to the representation of architectural space. We expect that a comparison of these two groups will help us to understand where architectural film and animation can go. We hope this understanding will (1) assist architects to specify filmic

representations of architecture; (2) provide further inspiration for creativity in architecture; and (3) inform computational design of unfilled gaps in software support for design.

This paper presents the results of our exploratory question "What do architects think about space, and about architectural film and animation?" Our interviews with filmmakers about how they handle architectural space are ongoing at the time of writing. Thus any comparison of how architects versus filmmakers approach space is for the future. Nevertheless, this paper presents the ideas of space as spoken by 17 architects, and shows that the practice of architectural film and animation has yet to reach its zenith.

2. Background and methods

We contextualised our research within previous work on architectural animation, like Rafi's (1998) study of architectural animation in architectural firms, and works of Kwon and Nagakura (2004), Alvarado (2008), and Chatzitsakyris and Nagakura (2005), which associated camera movements with spatial forms. Our overall plan was to interview both architects (some with experience in architectural film and animation) and filmmakers (mostly ones who have portrayed architectural space). This current paper, however, will focus on the concepts of architects in regards to this matter.

To understand filmic representation of architectural space, especially by architects, we also need to understand the concerns that architects have about space. We initially devised a collection of parameters that appeared to govern architectural film and animation, and gathered an extensive list of spatial archetypes that have two aspects: form and experience. That is, we selected forms that can be revealed sequentially by means of camera movement. We found archetypes in architectural literature, and in film. The film shots provided further examples of archetypal forms, and supplied them with associated typical camera movements.

The interviews with architects proceeded as follows: (1) they viewed a set of images, films, and animations depicting buildings and spaces; (2) they were asked to describe the spaces and explain what they thought was important in the viewed content; (3) they were asked to describe how they thought the spaces should be animated or filmed; and, finally, (4) they were asked to recall and describe experiences or films that left strong impressions of space. The architects were encouraged to express whatever they wanted to say on the subjects of space, and space in film. Table 1 shows where the 17 architects received their architectural education, and other architecture-focused experience.

The analysis was by *qualitative description* (Sandelowski 2000). Note, an inherent property of semi-structured interviews is that not all topics are discussed at the same level of detail with all of the participants. Resulting concepts rely on the rhetorical power of their evidence. We read the interview transcripts for the architects' remarks on (1) space, and (2) architectural film and animation. Then, within these two categories, we inductively grouped and arranged the remarks according to concepts that they seem to exemplify. We also read the transcripts for remarks that could be examples of the use of our spatial archetypes.

TABLE 1. Architects Interviewed.

	Architectural Education	**Other Architecture-Focused Experience**
RL	Canada	Animation, education
RW	USA	Education
NS	Pakistan	
RS	Mexico	Some animation
JP	Serbia	
DM	USA	Experimental animation
MK	Canada	
MM	Iran	
VS	India	Little animation
YN	Saudi Arabia	Animation, graphic design, education (architecture and design firm owner)
EM	Saudi Arabia	Education
SM	Saudi Arabia	Education, animation for several projects
SG	Saudi Arabia	Education
AH	Saudi Arabia	Education
BS	Saudi Arabia	Education
RK	Iran	Photography, some animation
DQ	USA	Photography, animation

3. Results

We first present our findings on architects' concepts of space, and then we present their approach to animation, where there is general consensus, and on what they differ.

3.1. ARCHITECTS ON SPACE

Overall, the architects blended their discussion of space with consideration for designed dialogue, context, and non-geometric ideas of space that contrast our spatial archetypes. We take all these concepts to be inseparable aspects of *architectural space*.

Designed dialogue: Architects will subjectively *read* a building for its design, interpreting from the building's manifest forms the organising system that generated it, such as the sense of order, or whether it adhered to minimalism, and so on (RW RL JP). The participants were generally unapologetic about their subjective approach. To them, a space was a designed dialogue between its various qualities—old/new (RS JP MK), inside/outside (MK NS RS JP MM DQ), private/public (RS), solid/transparent (JP DM MK), intimate/open (SM), natural/man-made (NS), material qualities such as texture and reflection (NS AH), and conventional/unconventional (RW JP). Responses varied when the work was a structural masterpiece (JP), or sacred (SM BS SG), exhibited glory and pride (EM), or inspired "awe" (MM YN SM). They were also aware of social contrasts that some works involve, like the co-presence of rich and poor in public places (EM). The modes of dialogue include juxtaposition, and sequential revelation (SM)—where travel through a space can conceal and reveal other spaces. The architects were sensitive to whether a space is best presented in terms of textural experience or as conceptual form (RW MM).

Context: Their description of architectural spaces usually included the context of the spaces. Context includes historic background (RS), the purpose of the building (RS MK), and the site where it is located (RS). The designed dialogue may include the context; the building's views may frame the exterior (MM); its forms may play off the landscape (DM); a tiring walk up a hill to get to a building is part of the character of the building (AH).

Architectural space: Form in space was, unsurprisingly, central in the architects' concerns. Architects themselves will claim that they think primarily in terms of disembodied, abstract, functional, geometric forms and 3D models (DM MK SM). Nevertheless, they were concerned about far more than pure geometry. For example, they brought a variety of terms to bear on the notion of scale. They talked of scale as being a means to understand relation (DQ), such as the difference between human scale (DM) and small scale (SG AH BS) or urban or architectural scale (DM). Scale shows magnitude (DM). It can get larger as someone approaches it (DM). RL talked about the Taj Mahal of Agra seeming close enough to touch, as seen and framed from inside the main gate, because (1) geometric alignments in perspective form flat-looking patterns, and (2) only blue sky can be seen behind it, so it "forms its own

horizon." Then, as one steps forward out of the gate, breaking the alignments and seeing the surrounding buildings, the Taj becomes both huge and far away in the landscape. YN talked about scale invoking dread, while SG, AH, and BS (interviewed together) mentioned scale as experienced versus the sense of scale as conveyed through TV.

There must be "space to breath" (NS). Space includes distancing and placement (EM), and has a perspective effect (RL MM). Not only must different spaces be recognisable, their social purposes must also be recognisable (RL). How people circulate through spaces is important, and must be self-evident to them (MK RL)—"the lines lead you" (JP). RL talked of space being generated by area around visual points, and lines by eye movement from point to point. The experience of architecture has key moments (RL MK DM) and key spaces (MK). Lighting is crucial to the experience of space (RL SM MM). All the architects talked of details as an integral part of the experience of a space; for example, the details of how things come together (DQ). Memory is also an aspect of experiencing space, not only to navigate and appreciate the contrasting qualities in succession, but also to return to a place much later to find that it has changed, and to try to remember was it was like before (AH).

Spatial archetypes: Our spatial archetypes comprise *open space*, *landmark*, *shaft*, *court/rotunda*, and *path*, *grid*, *labyrinth*, *shaft*, and *court/rotunda*. Path includes *arcade/nave*, *tunnel*, *clearance* (movement down a path from a constricting space to an open space), *layered* (a path that is accessed visually, with a beginning here, and an end there, with framing layers in between).

We found that when the architects referred to spaces that could be classified according to our archetypes, they spoke in terms of subjective, experiential, and (especially) emotional effect. For example, RL on the Ayah Sophia approaching a sense of sublime *open space*: "The size gave the feeling of awe. Made me feel like nothing. Nations and empires, leaders have come and gone. And I am nothing. The dome sits on skinny legs, and I felt a totality of space." Similarly, SM mentioned how a closed space will frame an open space (*clearance*), on one hand the closed space giving a sense of security, and on the other hand giving a sense of "wow" when one passes into the open space. Both JP and BS recalled *tunnels* that were used to deliberately evoke disturbing emotions. EM talked of *layered space* as being still.

While most talked about *path* in the context of architectural film or animation, RL explicitly talked about path for the design and experience of architecture. He drew on a white board the path between a gate to the Taj Mahal to the Taj itself. He laid down the significant points on the path, from right (the gate) to left (the Taj), then laid down a layer of information on those points, from left to right, and then laid down another layer of information, from right

to left. Similarly, his video of the same, comprising a sequence of cross-faded photographs of the Taj with overlaid graphics, passes over the path sequence twice with different graphics each time (Smith 1994).

3.2. ARCHITECTS ON ARCHITECTURAL FILM AND ANIMATION

Purpose driven: Because an architectural film or animation is not the prime artefact, the effort spent on it and its style suffices to serve its intended outcome (YN DQ). For example, an animation might be used, to give an idea of a building's shape (*turning table-top* animation) (YN), or, to impress a potential client that the architects are the right people to do a job (music video) (DQ), or show the geometric or computational techniques that produced the architecture (RL MM). YN associated realism with final marketing—"selling it on a map is difficult", and told of a case where someone abused realistic animation to sell real-estate that didn't exist. Many people have difficulty imagining 3D buildings from 2D images (YN NS DM). YN said that they don't do big animation for commercial purposes, only for internal use to understand design. EM used animation only for big, complex projects: at the conceptual stage for designers to visualise, criticise, and modify, and at a developed stage for clients to see textures and materials.

Building as artefact vs. building as experiential: The filmic treatment of a building depends both on the purpose of the animation and on the building. As mentioned in the section on space, the architects were sensitive to whether a space is best presented in terms of textural experience or as conceptual form. For example, RK talked about treating the Guggenheim museum as an artefact, highlighting its pure forms before moving into details. He contrasted this approach with treating a house more experientially.

Dominant approach for building as artefact: The dominant approach to portraying a building as an artefact is to first show the overall form—framing the building, its shape, on a large area by means of a bird's eye view (DM EM JP), focusing on scale, grandeur (AH), key structural things (MK) like façade, roof, closed or open spaces, contrasting spaces (DM), and symmetry (RK). Then the camera graduates to a human-level first person point of view to enter the building through an inviting entrance (MM RK), and shows key impressive design features and details (MM AH), focusing on certain natural responses, like when you look up at a ceiling (EM MM), or down at a floor (EM).

Diverse camera use: The architects demonstrated diversity in their discussion of how to use the camera. RM thought flythrough should have both high and low angles, whereas SM eschewed bird and ant angles as being "aesthetic" and having no emotional effect. RK claimed that wide angles should be used to show space, and still camera to show small spaces. SM and RK advised to

use many points of view and angles. The camera can move or zoom to show details or make something swell to fill the frame (DM JP MK DQ), and it can dwell on deep perspective (NS). Time lapse can show changes and uses of the environment (DM). The form of the space can constrain the camera, for example, a camera will likely follow a spiral and or rise up and down in the Guggenheim museum (DM). "Cuts are inserted when the space is boring, like a corridor" (RK). A presentation may also include 2D images, likely starting with the façade (EM).

Dominant smooth camera: They generally desired to make the camera smooth, if not continuous (AH DM NS); cuts should be minimal, and made to feel smooth. Yet the camera speed should exhibit variety (NS DM). Pacing is important (AH); RL talked about timing camera and action to coincide with the architectural features on which it is staged.

Camera path: Generally, the camera will follow a path (AH MM SM), that is a sequential revelation by means of a "realistic" *walkthrough* that observes a "logical order" of key shots (NS JP DM RK MK); a human does not walk through walls (SM NS MM) (though DM talked about violation of the natural my walking the camera across water, and portraying a real space but from a dream point of view). Nevertheless, the actual sequence of spaces can be somewhat arbitrary in practice (observation of SM's work), or driven by the need to be dramatic, by, say, moving from a small space to a large one (EM). They differed on whether to be complete, or show samples of the spaces: "For us, we focus on the customer of a villa. I show him how beautiful the building is. I won't follow a path. I can immediately go to the bedroom and focus on the view. But if I'm doing this for a contractor or a bigger company, I have to show the path and all the spaces" (AH). In contrast to following a path, RW talked about a focus on moments—with sequence being somewhat arbitrary.

Desire to portray designed dialogue: When talking about architectural film and animation, the architects expressed the desire to portray the rich dialogue between a building's various qualities (explained in the section on space) (NS JP DM MK EM RK RS SM DW MM), and emphasised texture and light (RW MM JP AH). Mystery and spirituality were also qualities of interest to be portrayed (NS MK AH EM), via dim lighting, night, twilight, low ceilings, labyrinth, secret doors, and sound. Finally, some were interested showing by animated transparency what could not be normally seen (RL NS DQ).

Use of human figures in space: "People are props" (DM). "Viewers can't imagine or understand space without seeing people" (RK). They provide aesthetic realism (SM RK MM), and scale (AH). They are used when the place would look dead without them (AH). They are shown at particular moments when they interact (DQ), or are doing meaningful actions (SM AH). One should

show their flow (NS), eating and drinking (JP), shopping (MK), happy in a spa (RK), romantic scenarios of friends and couples (SM). However, people can distract from the space (AH). Don't show too many of them (SM). MM and EM expressed discomfort with showing any people in private or semi-private areas (MM EM). AH said they should not be used in religious buildings. "If you want to show something as a spiritual place, you should remove this crying baby sound. … Don't show people lying down, or beggars" (SM). AH was interested in using people to show the effort of walking uphill to get to a particular building. In contrast to "people as props", JP suggested interviews with residents, and MK suggested a tour given by a receptionist.

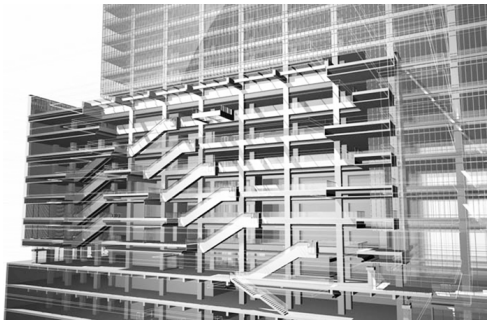

Figure 1. Jianbbei atrium cut away, courtesy Davis Marques.

Spatial archetypes: Path was the most obvious spatial archetype that the architects indicated, but here as a camera path as opposed to a feature of architecture. They widened *objects of interest* (a subcategory of *landmark*) to include *narrative objects*, such as moving curtains suggesting blowing wind (EM), suggestive sounds (AH), and "*atmosphere setters*", such as a flying birds (SM).

Critique of 3D architectural animation: DQ critiqued 3D architectural animation, pointing out that 3D animation rarely gives more information than a still image, and spoke of the unfounded desire for 3D animation and flythrough as arcane. "If I stand at one street corner, and I walk down the street looking at a building, I probably understood the shape, form, organisation, material, texture, and the exterior in the first few seconds. I didn't need that whole walk-along." Flythrough has redundant information, whereas the goal is to maximise the information from an animation. Furthermore, although "it is easy now to do realistic rendering, that is not necessarily a good thing; it is an issue of focus and communication." 3D animation is rarely worth the significant cost and effort. (Due to lack of skilled people and considerable

cost and effort, EM outsources architectural animation). DQ favours a mixed approach to telling stories in space that relies primarily on cross-faded stills usually producing a "30 second quick narrative through a series of views of a project." Animation (mixed approach) "unfolds experiences" that "have an element of time, that necessitate using animation and video to talk about how things change as one interacts with different pieces within the architectural space" (DQ).

4. Discussion

These are some of the recommendations we found that address the dialogue between the way architects think about space, film and animation:

Better understanding of the mismatch between what architects desire to show and the film techniques that they use: As experts in their field, architects showed a nuanced understanding of architectural composition and a deep concern for how people experience it. This understanding seems to defy easy categories, though our initial spatial archetypes were recurring terms. We thought that they would know less about film technique than what we found. We presume that the their approach to animation is what they think is effective. Unsurprisingly, there was a mismatch between the things architects said about architecture (the rich designed dialogues) and how they spoke about rendering architecture as a moving image— architects don't know how to connect film techniques to architectural ends. Now we have a better idea of that mismatch. To illustrate, architects think that a building should be presented in a logical spatial order. However, this logic turns out to be somewhat subjective. For example, architects think it is important to capture the "wow" of moving from a constricted space to an open one. That is, we believe that architects are more interested in showing the subjective impact of a design than showing one space then another just because they are beside each other. In many cases, subjective impact is best communicated by editing, but very little was said about editing (e.g. shot/counter-shot, cross-cut, split screen) or filmic composition (e.g. synchronic, diachronic, metonymy). Similarly, architects are very interested in including the dialogue between a building's various non-spatial qualities (old versus new, memory, recognisable social spaces, awe, mystery), but said very little about how they would do this.

Need filmic composition and editing: There are filmic ideas to explore in the context of architectural film/animation. For example, AH's interest in using people to show the effort of walking uphill to get to a particular building raises the notion of Gilles Deleuze's (philosopher of film) idea of the *time image*, in which we can see at a glance, say, someone's exhaustion, and thereby get an image of time, without having to view a whole episode. Similarly, RW's sug-

gestion to focus on moments was intriguing, because moments can become disconnected in time, and edge toward a kind of surrealism, like in Fellini's *Juliet of the Spirits* (1965)—a walkthrough can become the memory of a walkthrough, where the mind is free to skip around; disconnected moments can coalesce around special objects.

Need careful handling of people: Architect's seem to rely on mythical or shallow portraits of what people are like and do, in sharp contrast to, say, the studies of behavior in museums, or the studies of cooperative work. What would more careful portraits of people in architectural spaces reveal?

Drag and drop editing: CAD animation tools make it easy to run a camera along a spline curve. But, for architects to portray their nuanced understanding of architectural composition, and people's experience of it, they also need ready-to-hand editing tools. We cannot expect architects to become filmmakers, therefore they should also have easy access to libraries of example editing and composition. Imagine a scenario where an architect drags and drops an editing pattern onto a selection of spaces, and the system figures out how many cameras, how to move them and cut between them, how many frames to render, what lights and details to use, and more.

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REAL-TIME RENDERING OF LARGE BUILDING INFORMATION MODELS

Current state vs. state-of-the-art

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Abstract. With the use of Building Information Models (BIM), real-time 3D visualisations have become a natural tool in order to communicate ideas and share information between all involved parties in a project. Currently, several different BIM viewers are available for the purpose of interactive presentations and design reviews. However, as BIMs become larger and more detailed, it provides a challenge for available software solutions to manage them interactively. In this paper we present our findings from analysing three commonly used BIM viewers - Tekla BIMSight, Autodesk Navisworks and Solibri Model Viewer - in terms of real-time rendering performance. In addition we have developed a prototype BIM viewer to test modern approaches for efficient real-time rendering. Specifically, we have implemented the latest version of the Coherent Hierarchical Culling algorithm. Our results show that existing BIM viewers all share limitations in their ability to handle large and complex BIMs interactively. However, for the same test models, our prototype BIM viewer enables smooth real-time performance with no visual artefacts. The results from our tests thus shows that the technology to enable correct real-time rendering of large and complex BIMs is already accessible, but are currently not utilised by any of the tested BIM viewers.

Keywords. 3D graphics; BIM; real-time rendering.

1. Introduction

With the creation of Building Information Models (BIM), the content produced by architects and designers have evolved from traditional 2D drawings

and sketches to parametric, object-oriented 3D-models that can describe any building or facility in detail. As a natural extension, BIM further simplifies the use of real-time visualisations as a tool to communicate ideas and share information between all involved parties in a project. Currently, several different BIM viewers – both commercial and free – are available for the purpose of interactive presentations and design reviews. During these sessions it is desirable that the software can provide a smooth and interactive experience that is trustworthy. In other words, the system should be able to provide a sufficiently high frame rate without sacrificing visual correctness. However, based on our own practical experience with several of the available BIM viewers we have observed that this is not the case when large and detailed BIMs are used. Although some of these viewers have functionality to maintain interactive navigation by guaranteeing a certain frame rate, this is realised by presenting a visualisation that is incorrect. As BIMs tends to become larger and more detailed as the technology matures, we initiated a more comprehensive study within this area.

In this paper we present our findings from analysing three commonly used BIM viewers – Tekla BIMSight, Autodesk Navisworks and Solibri Model Viewer – in terms of real-time rendering performance. The focus is on large and complex BIMs and we have used several different test models to stress-test the available software solutions. In addition, we have developed a prototype BIM viewer to use as a reference and to test modern approaches for real-time rendering of large and complex 3D-models. Specifically, we have aimed for a solution that can provide both interactivity and correctness, even for large and detailed BIMs.

The rest of this paper is organised as follows. In the next section we briefly discuss a number of acceleration techniques for efficient real-time rendering. Section 3 presents our findings from analysing the existing BIM viewers in terms of real-time rendering performance. In Section 4 we motivate the choice of acceleration technique for our prototype BIM viewer and in Section 5 we present a performance analysis of it. Finally, Section 6 concludes the paper.

2. Acceleration techniques for real-time rendering

An important property for any type of real-time rendering system is its ability to maintain a sufficiently high frame rate. Although this number is highly dependent on the type of application, it is generally considered that it should at least be 20 Hz (Bittner 2002). Regardless, a too low or fluctuating frame rate will make navigation and other interaction tasks more challenging and may also cause participants to lose orientation or even feel sick (Yuan et al. 1997, Mortensen et al. 2008). However, depending on the amount of data to

be visualised this is not always an easy task to achieve. Even if the performance of computers and graphic processing units (GPUs) has increased tremendously during the last years there is always an upper limit in the amount of 3D-data that the technology supports out-of-the-box. Fortunately, a number of acceleration techniques exist that allows us to go beyond this limitation (Akenine-Möller et al. 2008). These techniques can basically be assigned into one of the following three categories: *GPU-centric optimisations*, *Level-of-detail* or *visibility culling*.

GPU-centric optimisation refers to several different strategies that are used in order to maximise the raw processing power of modern GPUs. Often, the impact on performance can be huge if the 3D-data is arranged and sorted in an optimal way before sent to the GPU. A typical example is to arrange the draw-order of objects by material properties. This will minimise costly state changes, such as switching shaders or textures, and let the GPU work with as few interrupts as possible. However, although efficient, the common characteristic of GPU-centric optimisations is that they do not reduce the amount of data that has to be processed by the GPU. As such, the approach is not indefinitely scalable.

Compared to GPU-centric optimisations, a more scalable approach is to consider Level-of-detail (LOD). With LOD, the main idea is to reduce the complexity of a 3D object representation when the object is far away from the current viewpoint. In such a situation the object becomes small on screen and a less detailed representation can be sufficient in order to give the same visual impression. The simplified version of the object is often created by reducing the number of triangles, replacing geometric features with textures or a combination of both. Regardless of simplification strategy the end result is an object that is less stressful for the GPU to process and therefore the real-time performance of the visualisation is increased.

Finally, visibility culling refers to a category of techniques where the idea is to improve performance by only sending objects that are potentially visible to the GPU. Today, most real-time rendering systems implement at least view frustum culling, where objects are discarded if they are found to be outside the visible region of space, as defined by the virtual camera. Although this approach can give a huge performance increase, it does not take into account a situation when objects in a 3D environment are entirely behind other opaque objects. In order to reduce workload in such a situation some form of occlusion culling has to be utilised. With occlusion culling the idea is to discard objects that are guaranteed to be hidden in the final image. The technique is considerably harder to implement compared to view frustum culling, but has the potential to increase performance substantially for 3D environments with

a lot of occlusion. As such, it is a viable acceleration technique for real-time rendering of building models and will be further discussed in Section 4.

3. Performance analysis and comparison of existing BIM viewers

In order to analyse and compare the existing BIM viewers in terms of real-time rendering performance, four different BIMs were used (Figure 1). Except for the A model, they all represent planned or existing buildings. The A model is an initial test model that, although not actually planned or build, may be considered representative for a student housing building. All four models were created in Autodesk Revit Architecture 2012 and exported to the IFC file format (BuildingSMART 2011). In Table 1, related statistics for all models are presented.

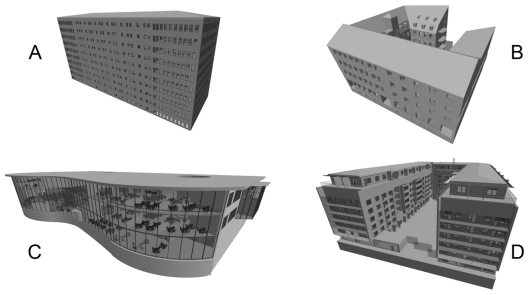

Figure 1. The four different test models.

TABLE 1. Statistics for the different test models.

Model	Type of building	Number of objects	Number of triangles
A	Student housing	5,683	9,559,028
B	Apartment building	2,151	1,474,586
C	Library / Culture building	6,224	4,102,959
D	Student housing	15,861	9,958,143

To measure the actual performance, FRAPS was used (FRAPS 2011). FRAPS is a software that "hooks into" the graphics driver in order to measure frame rate. The frame rate (in frames per second) is then displayed as a numerical value in the viewport of the currently active viewer. Unfortunately, FRAPS was unable to work together with the Tekla BIMSight viewer. For the Tekla BIMSight viewer we instead use a modified version of the GLIntercept software (GLIntercept 2011) that allows us to measure frame rates similar to

FRAPS. All the performance tests were performed on a computer equipped with an Intel i7 2.93 GHz CPU, 4 GB of RAM and an Nvidia GeForce 460 GTX GPU. The operating system was Windows 7 x64 and the viewport size was set to 1200 × 800 pixels.

In order to make a fair comparison of the different viewers in terms of performance, any acceleration technique that results in an incorrect visualisation is turned off. Specifically, both Navisworks and Solibri implements functionality in order to guarantee interactive frame rates during navigation. This is achieved by simply stop drawing objects once a certain rendering time has been reached. Although the rejection of objects appears to be based on its relative "importance" for the current view (size, type and distance to viewpoint) the approach does not guarantee a correct visualisation and often results in severe visual "popping" during navigation. Figure 2 shows an example of this in Navisworks for one of the tested building models when the desired frame rate has been set to 20 Hz.

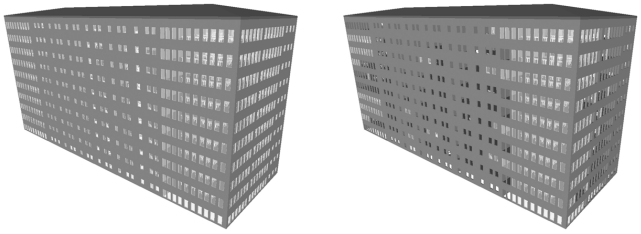

Figure 2. Visual artefacts (right) when forcing 20 Hz in Navisworks.

For all of the tests we have focused on the worst case scenario in terms of rendering performance. For all viewers this means a viewpoint where the complete building model is visible. In addition we have selected two interior viewpoints in all of our test models. These viewpoints represent neither the worst nor the best case in terms of performance, and should just be seen as typical locations inside each building. However, they do allow for a fair comparison between the tested viewers. In Figure 3, one of the selected view points (VP1) is shown for each of the models.

The results from our performance tests are presented in Table 2. Here, WC represents worst case, VP1 viewpoint one and VP2 viewpoint two for all of the tested models and viewers. The frame rates presented are consistent for the different viewpoints and any single spike or drop in frame rate has been omitted. Among the tested viewers no one except Navisworks appears to utilise any occlusion culling. However, during our tests it became clear that the occlusion culling in Navisworks is far from optimal and actually lowers

the frame rate in some of the tested models. We therefore present the performance results from Navisworks in two versions; occlusion culling activated (OCA), and occlusion culling deactivated (OCD).

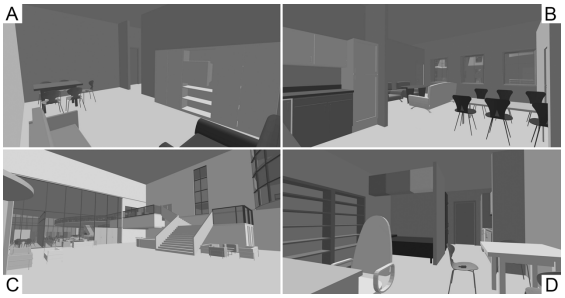

Figure 3. Selected viewpoint (VP1) for the different test models.

TABLE 2. Frame rates (in frames per second) for the four tested BIM viewers for models A to D: worst case (WC), viewpoint 1 (VP1) and viewpoint 2 (VP2).

BIM viewer	A (WC)	A (VP1)	A (VP2)	B (WC)	B (VP1)	B (VP2)	C (WC)	C (VP1)	C (VP2)	D (WC)	D (VP1)	D (VP2)
Tekla BIMSight	<1	5	3	5	12	7	3	7	10	<1	2	2
Autodesk Navisworks (OCA)	4	32	23	12	29	30	5	16	23	4	22	16
Autodesk Navisworks (OCD)	1	5	4	17	27	30	8	17	23	2	4	4
Solibri Model Viewer	26	59	52	62	80	129	23	43	42	8	11	16

When comparing the results it becomes clear that the Solibri Model Viewer offers the best performance among the tested BIM viewers. The tests further reveals a far from optimal implementation of occlusion culling in the Navisworks viewer, as it actually lowers the frame rate for many of the models. As far as we can tell, the higher performance of the Solibri Model Viewer probably comes from GPU-centric optimisations. As none of the tested viewers (except Navisworks) supports occlusion culling or LOD, the difference between them can only depend on their ability to utilise the GPU efficiently.

However, even if the Solibri Model Viewer turned out to offer the best performance, it was not able to provide sufficiently high frame rates for all of our test models. Although these models can be considered large and detailed, they are far from being a worst case scenario, even today. Taking future directions for the use of BIMs into account it should be safe to assume even larger models tomorrow. As such, a more performance efficient solution for real-time rendering of BIMs is required. The next section addresses the situation further by analysing potential acceleration techniques for our prototype BIM viewer.

4. A suitable acceleration technique for BIMs

As discussed previously, there are a number of techniques that can be utilised in order to accelerate real-time rendering. These have all strengths and weaknesses and a suitable choice is highly dependent on the type of 3D environment that it should be applied to. For instance, a vast, open landscape seen in a flight simulator is very different from a detailed city environment seen from the ground level when it comes to performance optimisation. For any type of real-time rendering system it is important to consider GPU-centric optimisations, such as efficient arrangement of draw order. Still, these techniques are only helpful up to a certain point. Once the 3D environment reaches a certain size in terms of amount of data we need an additional, more scalable approach. When considering BIMs, it typically contains a lot of rather small objects, such as furniture, lighting fixtures and sanitary equipment. When viewed from a distance these objects becomes very good candidates for LOD. However, even if this is a viable option in terms of accelerated rendering, it introduces problems in practice as it requires the existence of simplified 3D-models of all these objects. Although approaches exist to automate this (Garland and Heckbert 1997, Wang et al. 2009), it usually requires at least some user interaction and supervision in order to guarantee pleasant results for general 3D-models.

Another characteristic of BIMs is that they typically exhibit a lot of occlusion. For reasons that are obvious, a building is naturally divided into different zones, rooms and floors. Although some buildings, such as a concert hall or a library can be very open in their layout, there always exist areas that are separated, in terms of visibility, from the rest of the building. Given this, a suitable acceleration technique would therefore be to use any type of occlusion culling. Within this category several different algorithms exists that are mainly differentiated by whether they require time-consuming offline computations or not (Bittner and Wonka 2003, Cohen-Or et al. 2003). For the purpose of review sessions that require the visualisation to be initiated on-demand, an offline solution is clearly not the most suitable approach. For our prototype BIM viewer

we have therefore chosen to implement what is generally considered current state-of-the-art in terms of online visibility detection - the latest version of the Coherent Hierarchical Culling algorithm (Mattausch et al. 2008).

4.1. COHERENT HIERARCHICAL CULLING

Occlusion queries is a feature of modern GPUs that lets any application query the number of pixels that will end up on screen when rendering a specific set of geometries. This way, proxy-geometries can be used to test if any occlusion is present before the actual object is rendered. However, the use of occlusion queries introduces latency in the system which may lead to a decrease in performance if used naively. The initial Coherent Hierarchical Culling algorithm (CHC) (Bittner et al. 2004) makes us of temporal and spatial coherence in order to reduce this latency. In essence, this is realised by interleaving the rendering of objects with the issuing of queries while traversing the 3D scene (organised in a bounding volume hierarchy) in a front-to-back order. During traversal, queries are only issued for previously invisible interior nodes and for previously visible leaf nodes of the hierarchy. Still, for scenes with a low level of occlusion, the initial version of the algorithm can actually decrease performance (compared to only using frustum culling). To address this, CHC++, a revised version of the algorithm was developed (Mattausch et al. 2008). Although the core ideas remain the same, CHC++ introduces several optimisations which make it perform very well even in situations with low occlusion. For our prototype BIM viewer the revised version of the algorithm has been implemented, and in the following section we present a performance analysis of it when applied to the different test models.

5. Performance analysis of our prototype BIM viewer

For the performance test of our prototype BIM viewer we have used the same test models and interior view points as described in Section 3. As we utilise an efficient occlusion culling algorithm the performance is highly dependent on the view point we chose. For all of the models we therefore present the lowest frame rates that we have encountered during several interactive navigation sequences (Table 3). For the most complex model (D), we provide additional information about the rendering performance in Figure 4. Here, the frame rates are presented for a pre-defined navigation sequence when we are following a path around the building while the view direction is oriented towards the building. As the complete building is visible throughout the whole navigation sequence, albeit from different direction, it should be representative as a worst case scenario.

TABLE 3. Frame rates (in frames per second) for our prototype BIM viewer for models A to D: worst case (WC), viewpoint 1 (VP1) and viewpoint 2 (VP2).

BIM viewer	A (WC)	A (VP1)	A (VP2)	B (WC)	B (VP1)	B (VP2)	C (WC)	C (VP1)	C (VP2)	D (WC)	D (VP1)	D (VP2)
Prototype BIM viewer	100	800	700	260	500	450	120	285	400	94	550	300

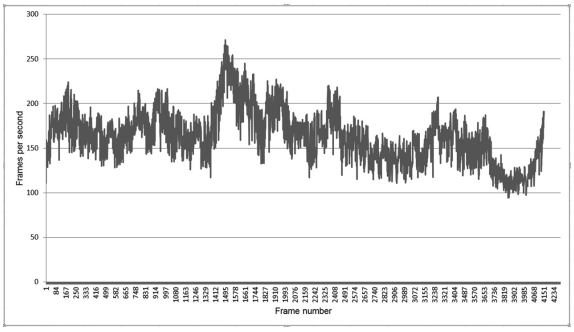

Figure 4. Frame rates (in frames per second) for our prototype BIM viewer for the D model during the pre-defined navigation sequence.

As seen by the result presented in Table 3 there is a huge difference when compared to that of the existing BIM viewers. This is especially true for the interior view points, but also for the worst case scenarios the performance is impressive. Even for the C model, which doesn't exhibit as much occlusion, the speed-up is almost 6 times compared to the Solibri Model Viewer. Furthermore, the data presented in Figure 4 reveals that, except for a small drop around frame 3900, the frame rate is above 100 frames per second throughout the complete navigation sequence. The tests thus confirm our assumption that an efficient occlusion culling algorithm is a suitable choice for real-time rendering of BIMs.

6. Conclusions

Regarding existing BIM viewers, our results show that they all share limitations in their ability to handle large and complex BIMs interactively. Although both Navisworks and Solibri Model Viewer implements functionality to maintain real-time performance during navigation, it is realised through rejection of objects that should, in fact, be visible. As a result, the presented visualisa-

tion is incorrect and exhibit visual popping. Without this acceleration technique enabled, Solibri turned out to offer the best performance. Still, it was not able to provide sufficiently high frame rates in all of our tests. However, for the same test models, our prototype BIM viewer enables smooth real-time performance with no visual artefacts. The results from our tests thus highlight the efficiency of the CHC++ algorithm and show that the technology to enable correct real-time rendering of large and complex BIMs is already accessible, but are currently not utilised by any of the tested BIM viewers.

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ESTRANGED-GAZE PEDAGOGY

Probing architectural computing through multiple ways of seeing

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Abstract. This paper discusses the challenges of teaching architectural design theory in a world transformed by the digital revolution. Design is changing in dramatic ways and architecture is changing with it but a well-defined body of knowledge that can serve as a foundation for digital architectural design has – as yet – not been established. Relevant concepts, methods and precedents originate in many fields that are typically well beyond the scope of reading suggested to (or encountered by) students of architecture. This material is highly dynamic, often contradictory and, typically, of varying quality. Presenting this developing body of knowledge to students is a difficult challenge. A suitable pedagogical approach ought to reflect the heterogeneous and volatile nature of the contemporary design discourse enabling critical analysis of existing design practices, evidenced defence of one's own creative work and successful communication with many heterogeneous stakeholders.

Keywords. Critical pedagogy; digital architectural design; architectural theory; architectural education.

1. Introduction: a conservative revolution

The current (late 2011) situation in architectural education is characterized by a growing number of courses focusing on the practical aspects of digital architectural design. These courses attempt to address the perceived need for new pedagogies that are – as the argument goes – based on "digital design thinking" (Chiu et al. 2003, p. 583, Oxman 2006, Iordanova 2007, p. 687) and "digital architectural theory" (Oxman 2008, p. 117) rather than on what is perceived to be outdated and inadequate paper-based workflows (Oxman 2006,

p. 249). Within this understanding, new pedagogies are necessary because the underlying concepts are themselves radically new: "dynamic concepts […] are creating a new definition of the role of representation" (Oxman 2006, p. 249), "digital techniques […] are forging new bases for design thinking" (ibid.) and newly categorized design approaches such as "topological design" contribute to a new "philosophical worldview that attempts to accommodate the new complexity of non-linear, networked conditions, and to depart from the more static and typologically deterministic logic and design methodologies of the previous generation." (Oxman 2006, p. 252).

I am sympathetic to the excitement generated by complex geometries and process-oriented approaches (and happily use them in my practice). If anything, they are supremely valuable as catalysts of what Caputo (1987) calls "free play" and Gallagher (1992) recognizes as creative transcendences into the unknown. However, I also cannot help feeling that confining the perceived newness to the field of architecture (taken as a given, stable and unproblematic entity) and – especially – to its form-making processes is a sadly conservative posture. Why do I feel entitled to such a counter-intuitive pronouncement, and how is it relevant to the field of architectural education?

An in-depth discussion of the relevant issues is well beyond the confines of this paper but – briefly – the failure to reconsider the boundaries of the discipline and the desire to satisfy the established expectations (even if in new ways) falls within what Coyne (1996, p. 1) discussed as an essentially instrumentalist/conservative attitude to practice and education. In architectural education instrumentalism can be associated with the constricting transmission model of education (Crysler 1995) and in architectural practice with what Coyne (1996) describes as lingering links to positivism and scientism. For example, witness the now-growing desire to justify the utilization of computing in architecture – for example as the generator of complex geometries – via bio-technical rhetoric of functional/physical building performances. Multiple citations can be provided (e.g., cf. Kolarevic and Malkawi 2005, Oxman 2008) as an illustration of this trend that Sinopoli (2010, p. viii) (in a professional book, admittedly) takes to an extreme that ignores all cultural, technical, political, logistical or ecological aspects of its vision: "[i]n due course buildings will become full of technology. Walls and ceilings will be embedded with sensors, and every aspect of a building's performance and use will be metered and measured."

Extending the established architectural history of styles, movements and personal philosophies with another new internal shift (e.g., parametricism) appears insufficient in relationship to the existing need. As Letherbarrow (2001, p. 85) observes, architectural knowledge is characterized by fragmen-

tation and co-presence of incompatible truth-claims. His conclusion is that architecture can only regain its authority, responsibility and cultural purpose by unmasking these truth claims and simultaneously redefining the understanding of architecture's subjects to suit current conditions. This task is greater than the commonly recurring discussion on "form follows software" (Serriano 2003, Terzidis 2009, p. xx), "form follows tool" (Rügemer 2008), "form follows media" (Asanowicz 2004) or even simply, "form follows…" (Iordanova 2007) (perhaps McDonough's (2002, p. 71) discussion of self-replication forms – such as books – following the evolution of the medium itself, Hill's (1998, p. 7) "form follows everything but function" or Mitchell's (Mitchell, 2003, p. 32) "form follows feedback" can be useful here as suggestive alternatives pointing to the concerns beyond form as form?). Conceptual shifts internal to architecture do not question the boundaries of the field or interrogate the issues of concern, instead creating a fashionable but – as before – perishable style.

Myopic understandings of architectural design persist alongside dramatic changes in the character of design in general. Increasingly, design is about leadership, team-building and campaigning rather than about artifact-making, individual inspiration and style (e.g., cf. the rhetoric by NextD or IDEO). By contrast, the encompassing discourse on technology begins to suggest that designerly approaches to knowing can offer unique contributions but that their agency depends on broad cross-disciplinary integration (e.g., Thackara 2005) and on the rethinking of design contributions in inclusive terms. This inclusiveness does not neglect the contingencies of cultural/social meaning construction (e.g., Verbeek 2005) and sees the outcomes of design in terms of power negotiations (e.g., Fuad-Luke 2009), discursive events (e.g., Krippendorff 2006), dynamic relationships between human and non-human actors (e.g., Latour 1996), etc., – it would be easy to continue.

Courses that deal with conceptual implications of computing in architecture are commonly embedded into long-established programs that not only inherit most of their content from the pre-digital era but also have a tendency to be bounded by the concerns of the architectural profession as it exists today. This grounding in history and linking to professional practice are necessary. However, they can lead to the exclusion of significant discourses that situate and critique digital technologies. Given the growing role of digital technologies in redefining many of the core social practices, a failure to consider their emerging and possible implications will increasingly curtail architecture's capabilities for envisaging and provoking possible futures.

Traditionally, the task of conceptual exploration in architectural education is fulfilled by dedicated "history and theory" modules. In our survey, which

included students from the University of Melbourne and Royal Melbourne Institute of Technology (RMIT), two themes were apparent. Firstly, none of the existing history and theory courses explicitly focus on computation and its implications. Where references to projects using digital technologies are made (with typical examples including Greg Lynn or Frank Gehry), they are discussed as variations in recurring stylistic fluctuations. In the instances where relevant discussions do occur, they focus primarily on "aesthetic capacity". Consequently, students report that the majority of their peers do not understand the fundamental implications brought about by digital technologies. My own observations suggest, furthermore, that even where more advanced students claim greater familiarity with the contemporary theoretical discourses, they omit many areas of research and experimentation that extend beyond the challenges posed by complex geometry. In a popular phrase, they do not know what they do not know.

2. Method: thinking through (teaching) practice

Undoubtedly, the relevant pedagogical offerings will multiply and the discussion on what is relevant will grow. This paper aims to contribute to this process by deriving arguments from one particular example – the *Production of Digital Space* course at the University of Melbourne. I first encountered this course when I arrived to the University in 2009. It was invented by Bharat Dave as a member of a triad of master-level electives (excuse simplistic descriptions): *Digital Design Applications* (focusing on scripting), *Contemporary Digital Practice* (analyzing professional case-studies) and *Production of Digital Space* (engaging with theory). My assignment was to share the responsibility for these courses and I began by taking over *Production of Digital Space*.

The opportunity of teaching such a course can be understood as the challenge of understanding (and questioning) the general institutional context and the course-specific inheritance: the triad superstructure, the theory orientation, the ringing course title, the deliberately flexible handbook outline and the didactical structure of a seminar. This paper cannot contain an in-depth analysis of this pedagogical engagement. Instead, the experience of teaching this course provides an illustration of sense-making, in real-world circumstances. Consequently, my observations have no ambition to form a generalist framework directly useable by others. Instead, they seek to contribute by (1) asking familiar questions in specific conditions; and (2) providing and justifying idiosyncratic answers. I hope that this exposition can provide fuel for the ongoing (and necessary) conversation on the issues at stake.

3. Theme: what is theory?

Given that this paper emerges from a practical experience of teaching a course intended to engage with theoretical implications, it is prudent to briefly consider the very concept of theory.

Hays (1998) understands theory as a practice of mediation or "the production of relationships between formal analyses of a work of architecture and its social ground or context […], but in such a way as to show the work of architecture as having some autonomous force with which it could also be seen as negating, distorting, repressing, compensating for, and even producing, as well as reproducing, that context." Hays bases his understanding on Jameson's (1981, p. 40) notion of mediation as a particular way to analyze distinct levels of reality. In this view, mediation is a device of the analyst. This device is able to overcome – even if only in local and specific circumstances – the apparent fragmentation of social life. Such devices can be valid only because "social life is in its fundamental reality one and indivisible, a seamless web, a single inconceivable and transindividual process, in which there is no need to invent ways of linking language events and social upheavals or economic contradictions because on that level they were never separate from one another."

Thus, the linking or making of relationships is the central capacity of theory. And yet, this capacity is undermined by what Agrest (1991, p. 1) perceives as "an absolute separation between theory and practice […]". She sees the difference between theory and practice as the dissimilarity between discourses (analytical, exploratory, critical on one hand and normative on the other) but for her the separation remains very real.

At the same time, another line of reasoning persuasively proposes that contemporary design's contributions are (significantly, or even primarily) to the discourse (broadly understood) (Krippendorff 2006, Schumacher 2011) operating within "experience economy" (Pine II and Gilmore 1999). Elsewhere, I have also argued (Roudavski 2008) that architectural output can be usefully interpreted in terms of situated performances supported by multiple actors. As Rampley (2005) suggested, "architecture needs to be thought of less as a set of special material products and rather more as [a] range of social and professional practices that sometimes, but by no means always, lead to buildings."

How do these conditions frame theory, especially in a pedagogical context? Multiple interpretations are possible but I find one particularly productive. This interpretation sees theory, practice and objects/subjects of architecture as cultural constructs, sustained by technologies and meaningful in human societies. This understanding allows one to focus on the discussion of situated techno-social performances in a way that transcends disciplinary or conceptual boundaries (e.g., between theory and practice, built environment and

nature, structures and media or architectural profession and other designerly ways of knowing).

4. Pedagogy: altered gaze

How does this conceptual position materialize in a practical pedagogy? This paper is too concise to go into details (which I am happy to share on request). Instead of explaining the particulars of the course, I shall, therefore, present a conceptual stance that considers the relationships between the teacher, the subject and the students as fluid and opportunistic.

I find the metaphor of vision tricks used in life drawing useful as a device-to-think-with. When drawing, one squints to simplify, turns the image upside down to check proportions, measures with a pencil in an outstretched arm to control scale, draws without looking at the paper (or even with the eyes closed) to decouple the trace-making from the conscious analysis and so on. People arrange their drawing studies as varying temporal engagements, from a 10-second sketch of a nude to a portrait of 20 sessions. They draw posed skeletons in anatomical theatres and pacing tigers in the zoos, outline with 5H pencils and paint wet on wet, etc., etc. These techniques are combined opportunistically according to the circumstances, often not with a purpose of producing a completed object but with the intention of amplifying one's understanding.

My pedagogy adopts a similar strategy – which encourages what I have called here an "estranged gaze". Accepting that it is not possible to cover the vast and volatile field of contemporary technology in any detail, I – instead – seek to provide students with an opportunity to capture it in their work. This capturing takes multiple forms, from essays to speeches and from charettes to extended research projects. This strategy is applied within the *Production of Digital Space* course but also extends beyond its confines, emerging as a loosely interconnected palette of teaching initiatives occurring at multiple levels of expertise, in different formats, between institutions and across professional/educational communities. Narrative lines cross the boundaries of individual courses and students can follow them if they so choose.

The *Production of Digital Space* course takes the form of a semester-long seminar series. Within it, students read, discuss and write essays. The seminar invites guest experts and encourages practical experimentation. Elements of this structure will be familiar in a variety of disciplines. More unusual (I would say innovative if I had better information on the courses taught by others – not many are described in existing literature) is its attitude to the selection of content. In the area where there are no established theories or practices and where most of the relevant literature is embedded into extensive and complex

multidisciplinary discourses, the course chooses to provide a strong narrative line exemplified by extensive lists of eclectic case-studies and readings whose main purpose is to estrange the participants' gaze and prevent the comfortable preference of thinking in conventional, discipline-specific terms.

To illustrate, in 2011 the course covered the following thematic areas (names in the brackets indicate the intellectual pedigrees): (1) *Lived Space*, or the discussion on the fundamental roles of architecture including its conceptualization as a system of performances with references to the extended and "fluid" nature of objects (cf. Annemarie Mol) and the understanding of places as dynamic and distributed (cf. Doreen Massey); (2) *Design Space*, or the discussion of designing as a unique way of knowing (cf. Richard Coyne), Design 3.0 (cf. GK VanPatter), distributed creativity (cf. Rober Sawyer) and contemporary visual thinking (cf. Birger Sevaldson); (3) *Representational Space*, or the consideration of digital phenomena as subjective constructs ranging from theories of montage (cf. Sergei Eisenstein) to *dingpolitik* (cf. Bruno Latour); (4) *Virtual Space*, from the boredom of architectural flythroughs to the architecture of massive persistent online games (cf. Espen Aarseth, Richard Bartle or Julian Oliver); (5) *Augmented Space*, including the discussion on ubiquitous and location-aware computing (cf. Tim and Jan Edler, Hiroshi Ishii and Malcolm McCullough); (6) *Parametric Space*, including generative approaches and their links to building performance (cf. Branko Kolarevic or Michael Weinstock); (7) *Complex Space*, or the discussion on artificial intelligence and artificial life (cf. Ernest A. Edmonds vs. Michael Hensel or Tom Verebes vs. Robert Venturi); and (8) *Networked Space*, including the consideration of objects with histories (cf. Bruce Sterling) and architectures spanning multiple places and temporal streams.

Throughout, the seminar exposes its leader's positions but includes texts and examples presenting varying and contradictory viewpoints. Many of the included items emerge from previous discussions and collaborative projects with students and colleagues within and outside of this seminar. As a result, students' research topics reflect the diversity of themes and the multiplicity of scales: digital architecture and nature analogies, resistance to digital design in architectural practice, gamification, parametricism, videogame architecture, copyright and authorship, participatory design, early design and computation, responsive materials, commercialism in cyberspace (Roudavski and Parton 2011), local optioneering (publication forthcoming), computation in building construction, spatial behaviors, robotic fabrication, virtual geographies, ornamentation, science-fiction architecture, augmented everyday, habitation in hybrid/virtual space, self-replicating structures, gestural interfaces, etc. I cannot demonstrate their quality here (some are published/exhibited/awarded

while others are – well – basic) but hopefully, they show the participants' efforts to reach out.

5. Conclusion: looking and seeing

According to the students' feedback, the strategy of probing into multiple, far-reaching topics produced significant shifts in their understanding of design and technology or broadened their outlook on what is relevant. This is encouraging but – for me – unsurprising because my frequent impression is that most contemporary students (I am told students used to be rowdy in the days gone by) are more conservative than their teachers and – something this course is trying to disturb – immersed with no second thoughts in the intro-architectural concerns. Given this, I take their willingness to risk an unfamiliar topic and the demonstrated readiness to engage as success.

The experience of teaching this course suggests that patchwork pedagogies engaging with multiple perspectives and degrees of magnification might be useful as sites of critical analysis, disagreement and comparative sense-making. By accepting the plurality of engagement as the primary characteristic, this approach seeks to provide the experience of seeing differently in the hope of equipping the students with the confidence to assemble their own interpretative systems from whatever tricks seem appropriate, whatever the initial complexity and ensuing confusion.

A chance to consider relevant, questionably relevant and frankly "out there" issues encourages unorthodox thinking about career paths, business models and cross-disciplinary collaborations. When this thinking is tested through thought experiments, case-study analyses, critical writing and practical work, participants gain a chance to accumulate creative expertise and construct alternative track records that can serve as evidence in discussions with uninitiated others. Such discussions are going to become more common if – as commonly predicted – design complexities will continue to increase, necessitating regular exchanges with collaborators acculturated into different languages and value systems. In these situations, an ability to justify creative decisions and translate between domains will prove especially valuable. This is already evident in the situations where students need to explain and defend their experimentation (commonly that with complex geometry) during design crits, sometimes in the face of (variously justified) skepticisms towards most things digital. As one student stated in an answer to the question "has the course influenced your outlook on the digital technologies and why/how?" – "[y]es, I have a greater sense of the wider cultural attachment of digital practices discussed in the subject and the […] grounding many of the technologies have in theoretical discourse. This has provided a degree of validity to an

area otherwise referred to in purely aesthetic or insubstantial terms within the university environment, which I found helpful to furthering my interests and capacity to contribute."

These ambitions are in line with the overarching conceptual outlook that sees the goal of education in transformation and capability building, not in the delivery of information. This, once again, is a move aimed to overcome the divide between theory and practice by making the outcomes of a theoretical course become meaningful as enablers of design or – in Perkins's (2008) classification – "proactive knowing".

The work in this area ought to continue and I would be very interested to hear of the strategies employed by others.

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TAGGED AND INTERACTIVE DIAGRAMS OF DESIGN INTENT AND RATIONALE

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Abstract. This paper describes our experiments with diagrammatic representations to think about design compositions and to learn from shared accretion of design knowledge. We describe here implementation of an online prototype that, on the one hand, offers interactive functionalities to externalize thinking about design compositions in the form of diagrams and, on the other hand, which acts also as a repository of diagrams that can be dynamically interrogated to find other proximate compositional thinking and ideas related to a particular design position. Put differently, the prototype helps both notate design thinking and draw out associations between separately notated design thinking.

Keywords. Diagrams; compositional logic; design representations; knowledge accretion; reflective thinking.

1. Introduction

Although different in materials, components, governing geometry and visual character, the three objects shown below share a common interest to explore the concept of '*series*'. The presence of such shared threads across projects – either in the final material assemblies or in how they were made, may be sometimes hard to notice. But once recognized, they open doors to further fruitful experimentations and explorations in design. To foster recognition and use of such higher level generalized concepts and operations in design, we developed an online repository of diagrams that is *associative*, *incremental* and *dynamic*. The online prototype system helps both notate design thinking and draw out associations between separately notated design thinking. This paper describes motivations that informed the design and implementation of the prototype, its benefits in design projects, evaluation of its use and plans for future extensions.

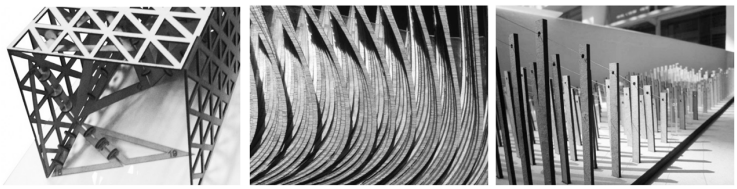

Figure 1.'Series' projects.

1.1. PROTOTYPE IN ACTION

The following figure illustrates main interface components of the implemented prototype. The left-half of the figure shows an image of a fabricated model for the currently selected design project and its associated diagram with design and fabrication sequence. The right-half of the figure shows a number of image tiles of other projects in the repository. Each of these image tiles are clickable and act as pointers to access different data associated with each project (as displayed on the left half of the interface).

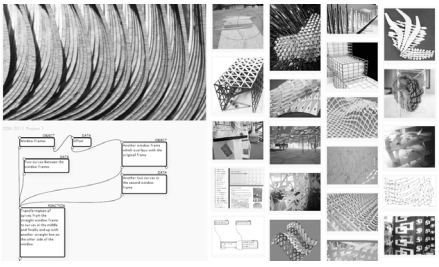

Figure 2.Prototype overview.

2. Motivations

Our work is motivated by a number of intersecting ideas and observations, many of which are noted earlier by other researchers. There is increasing acceptance and appreciation for the need to support interactive 3D modelling using both direct manipulation and symbolic languages (as in scripting and programming languages). The burgeoning interest in interactive exploration of parametric design spaces has once again fore-grounded work in extending and integrating visual programming paradigms of the past with complex interactive 3D geometry modellers. These developments enable relatively novice users to exercise much greater expressive power in a short period of time. However, it also requires that users conceptualize and understand how to operate simultaneously between different representational spaces ranging from graphical, numeric, symbolic, and others.

Although initial learning curves for such interactive modelling tools may have become less steep, users may not find it easy to express and control anything but simple spatial compositions. The ease of visual programming is often replaced by incomprehensible clutter of symbolic graphs wherein interdependencies become hard to follow or trace and distilling generalisable knowledge may become difficult if not impossible in a forest of details. Also the frequent and continuous updates of software work against possible accretion of shared practices and reusable code.

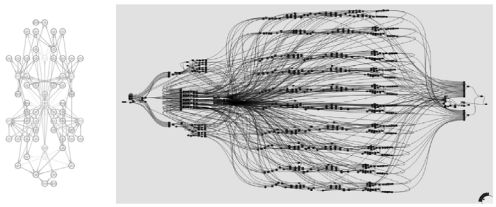

Figure 3. Spaghetti of symbolic representations.

When the preceding issues with visual programming and modelling systems intersect with architectural design and representations, they become more problematic. Since the very purpose of design is to generate something that does not yet exist, iterative design emerges as the preferred mode of practice. In this context, support for version histories may be expected to encourage parallel and divergent exploration of design alternatives using scripting or programming environments. However, the significant amount of effort required for managing complexities of digital representations and operations in a design project very often propel projects along a singular developmental trajectory. These issues become apparent, albeit with varying intensities and forms, while teaching architecture students to design by scripting. Ideally, such undertakings in academic and professional settings should be accretive, exploratory, and independent of particular software environments. They should be accretive, i.e. build on others' work rather than always start from the same low thresholds. They should be exploratory in that they foster divergent and lateral thinking rather than rapidly converging on to a solution at least in the early design stages. And they should foster higher-level compositional skills rather than be constrained by software instrumentalities.

2.1. RELATED IDEAS

Our work draws upon a number of recurring themes in development and adoption of computational approaches that respond to particular needs for design representations and modes of thinking. The notion of patterns in design appears

in literature from vernacular architecture (Alexander 1977) to formalized rule books (Durand 2000). The notion of levels of abstractions in design appears from cognitive studies of designers (Gero 1998) to pedagogical traditions in design (Fischer et al. 2000). The notion of internalizing and using design moves of various grain sizes appears in the context of how designers think to how users develop models of software systems and how effectively and efficiently they can use those tools (Coyne et al. 1993, Pantazi 2008, Maleki and Woodbury 2010, Woodbury 2010). Our work builds upon and extends these ideas by developing a particular set of ideas and testing it in the form of an interactive, incremental, online catalogue of fragments of design thinking at a level of abstraction that is independent of constraints of specific languages, tools or materials.

2.2. FOCAL ISSUES

An underlying interest in understanding and distilling higher level design thinking guided a number of studies cited above. These efforts have led to development of some promising tools and environments such as the visual programming environment of Grasshopper or in-place scripting supported in Generative Components. While these and other similar efforts are promising, we are interested in one particular cluster of issues: how to foster higher level compositional design knowledge without being too closely tied to a particular implementation, one that supports divergent thinking and allows associative exploration of ideas, and one that can be incrementally added to over time. Further, we wish to emphasise thinking about design compositions as a *process of making* and not just as a penultimate state description as in traditional design drawings. The above issues informed development and implementation of an online prototype that, on the one hand, offers interactive functionalities to externalize thinking about design compositions in the form of diagrams and, on the other hand, which acts also as a repository of diagrams that can be dynamically interrogated to find other proximate compositional thinking and ideas related to a particular design position. It should be added here that diagrams are but one among many other useful representations to notate design thinking – prior to, during and in retrospect.

3. Prototype architecture

The prototype system comprises a set of interconnected components. A standard WordPress installation is used as the primary backend component which supports composition of different data types including text, images, video, and others in the form of posts and pages. Diagrams are added to this collection

of media types using an interactive diagram builder implemented in Flash. This component also allows grouping of diagrams (displayed as tabbed pages) based on a simple naming convention. The diagram builder is integrated with PhP which turns text strings embedded within diagrams into *tags* similar to how they are used in the standard WordPress metadata. The automatic tagging of text chunks in diagrams allows specific instances of various data and also entire posts to be associated with each other. The front end is managed using a combination of PhP scripts and JQuery functions to generate dynamic CSS/HTML code that formats and renders user-level information display.

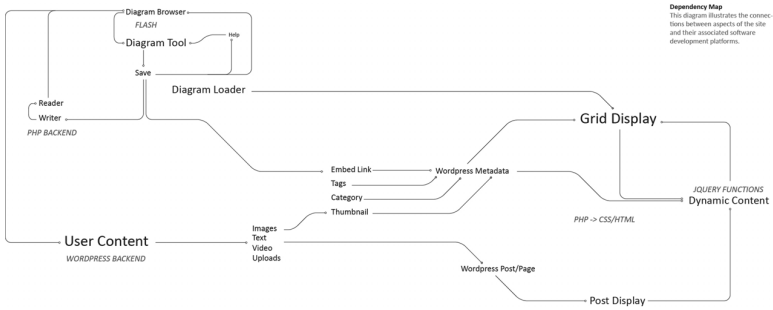

Figure 4. Systemarchitecture.

4. Prototype functionalities

The prototype system revolves around three kinds of users with different privileges. The ‘reader’ role allows anyone, anywhere on the net to browse and query different information chunks including diagrams. The ‘creator’ role enhances ‘reader’ privileges with creation and modification of diagrams and posts generated by a registered user. The ‘admin’ role has all the privileges including moderation and publishing of diagrams and posts.

4.1. DIAGRAM CREATION

The interactive diagram builder supports a small number of named container nodes (represented as rounded rectangles): data, function, object, image and fabricate. Data nodes contain parameter(s) or variable(s) that are used by other nodes. Function nodes represent a series of operations, possibly using data received from and passed to other nodes. Object nodes represent repeatable elements, e.g. a panel or a rib, with variable properties. Image nodes point to locally stored or network-accessible image/video data. Fabricate nodes represent specialised chunks of operations to translate generated geometry to suit the needs of specific fabrication technologies and tools, e.g. laser cutter, 3D

printing, etc. Each of these nodes has two connectors at top left and bottom left corners which represent input and output to/from nodes respectively.

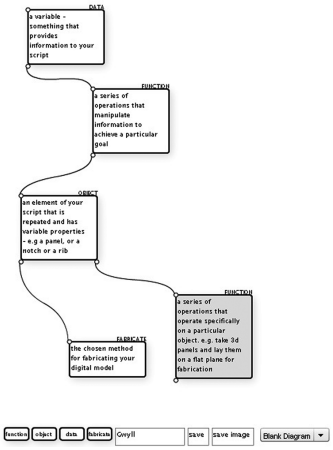

Figure 5. Diagram builder and nodes.

To create a new diagram, nodes are dragged out from the toolbar onto the blank canvas. The flow of information between nodes is represented by drawing a connection from output (bottom left) connector of one node to input (upper left) connector of another node. The nodes can be annotated using free form text which is displayed inside the node rectangle. The nodes can be repositioned manually anywhere on canvas; the connecting edges between nodes are maintained by the system.

4.2. USE SCENARIOS

Our prototype implementation supports declaration of compositional intents prior to, during and retrospective to a design project. This is facilitated by interactive composition of a series of diagrams by the user, each of which may be associated with other design diagrams via ‘tags’. The dynamic repository of diagrams conceptually resembles ‘tag clouds’ of design intent and rationale. The uses and benefits of the implemented interactive prototype are briefly described and illustrated next.

4.2.1. Modular thinking

The use of diagrams fosters modular thinking about design moves in terms of required design elements and operations on them (Figure 6, left). It encourages a degree of higher level meta-designing instead of being caught up with all the

details simultaneously at a small grain size. The explicit recognition of input and output data reinforces the notion that design compositions are materialized outcomes of a temporal assembly process and that *correct sequence* matters (in the sense that each distinct sequence may lead to unique outcomes).

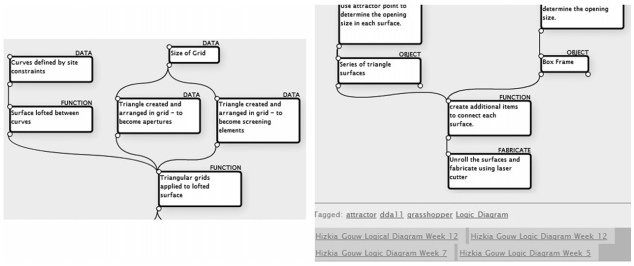

Figure 6. Left: Sequenced and modular design moves. Right: Tabbed idea histories.

4.2.2. Idea histories

A series of diagrams supported by our prototype enables occasional look back and (re)tracing of paths followed and perhaps discarded. The use of multiple, alternate diagrams (Figure 6, right) encourages what-if explorations in design and provides a concise record of design history that mitigates against early idea fixation and encourages reflective assessment.

4.2.3. Proximate ideas

The tagged associations between diagrams bring to fore proximate design ideas, a difficult thing to achieve in analogue and discrete representations. The tags operate at two levels. When used as a search term in the main interface (as in Figure 7), the system highlights all projects that are similarly tagged. When used from within diagrams by clicking on a string (for example, 'series' as in Figure 1), all similarly tagged projects are highlighted.

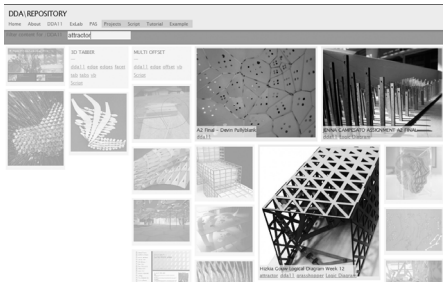

Figure 7. Query and display of proximate design ideas.

4.2.4. Grain size of representations

Diagrams enforce choices about grain size of representations and thus help reinforce thinking about when and how to generalize or disambiguate specific details. This has played out in our system in two ways. Since the diagram builder provides only a limited canvas, users become selective about what to describe in diagrams with brevity and clarity. At other times, users develop a working script first, draw the diagram, and then update their scripts as the next reflective step.

4.2.5. Recombinant fragments

Diagrams as fragments of design intents and operations make possible creative puzzle-making in which fragments may be recombined to form new design compositions on the fly. This is enabled by tagged searches (Figure 8) and the possibility to combine parts of other compositions or their design logics to generate novel design outcomes.

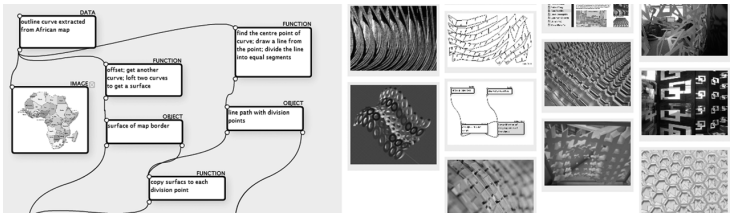

Figure 8. Pointers to local and remote data.

4.3. EVALUATION

The prototype system has been used most recently by a group of 20 students, many with no prior exposure to computational thinking or experience in scripting. The students faced two simultaneous demands: learning to script while also developing design ideas to be generated using scripts, and then fabricated and assembled. The students were asked to use interactive diagramming system as part of their project development process.

The feedback from a representative student group offers interesting insights about similarities and differences between traditional *designerly* ways of thinking and computationally supported explorations, and how the use of diagrams supported by our system mediates between the two modes.

Most students generated diagrams towards the end of their projects rather than as an integral part of design exploration from the beginning of their projects. This can be ascribed to the need to know what is possible (using

scripting) before deciding on what to design. As one student put it: "… *I was new to Grasshopper ... I didn't know and needed to work out what I didn't know*". As a result, she generated the diagram at the end, more as "*a description of process*" rather than as a "*planning tool*". However, having generated a series of diagrams, she "…*understood a lot more*" about both the range of design possibilities she could explore and also alternative computational procedures through which to realize them. This retrospective abstraction of her design project also highlighted the fact that what she explored initially in terms of design possibilities was limited by the handful of scripting functions she learnt which, in turn, limited her design ambitions. The use of diagrams allowed her to step back from these limitations and reframe her design intentions in a way that was independent of what she knew or what the function set of a particular scripting environment supported. The need to articulate and represent diagrams within a limited space – unlike the infinite scripting canvas – forced her to rephrase in "*clear and abstract terms*" the object of her composition and the sequence in which it was to be generated.

An experienced design student employed clusters of coloured nodes in his script which were then used as building blocks of diagrams he generated. This correspondence between a particular set of scripted nodes and their abstracted descriptions in diagram allowed him to better understand and explore the notion of generic types and specific instances.

A student with limited design and scripting experience noted: "… *in the beginning, I have no idea what I am doing or why*". The use of diagrams and the free form text embedded in diagram nodes gave him "*goals ... a direction*" to pursue, helped by looking at others' pseudo-code and diagrams.

Interestingly, another student commented that diagrams allowed him to reflect on similarities and differences between two different operations, such as *lofting* and *extrusion*, which may result in similar design outcomes but require different intermediate information and processing steps.

Finally, the use of diagrams forced students to articulate and communicate stage wise planning and making of material objects in ways that are substantially different from traditional design drawings since the latter act more as state descriptions of final outcomes and do not reveal processes of making and assembling components.

5. Future extensions

The growing numbers of projects in which the system is used and feedback received suggest a number of future extensions. One such significant extension will support embedding of diagrams within diagrams. It will help represent and foster thinking about design operations at multiple levels of details

and grain sizes, by collapsing or unpacking diagram nodes. A related extension will allow diagram nodes to directly point to pseudo-code of specialized components or generalized procedures/functions. Further, it will be useful to add suggestive pointers in the form of contextual pop-ups with freeform text strings as they are added to describe diagram nodes. Such pointers could suggest other visual examples, pseudo-code fragments, specific operations, packaged components or plug-ins. The common thread running through these future extensions is our interest in fostering design exploration by supporting divergent paths at as many points in the early design process as possible. We also wish to cultivate higher level thinking about design that is independent of specific programming environments.

Our prototype system is accessible to anyone from anywhere on the net whereas the ability to create and modify diagrams is moderated and restricted. Until now, the system has been used locally in advanced graduate design subjects; we plan to make it available to others in near future.

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This project has benefited from the work of a number of students in the Faculty of Architecture, Building and Planning, University of Melbourne during 2008–2011. The prototype is accessible online at http://scripts.crida.net/gh/dda11.

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DESIGN ENIGMA

A typographical metaphor for enigmatic processes, including designing

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Abstract. Presenting a hard-to-predict typography-varying system predicated on Nazi-era cryptography, this paper illustrates conditions under which unrepeatable phenomena can arise, even from straight-forward mechanisms. Such conditions arise where systems are observed from outside of boundaries that arise through their observation, and where such systems refer to themselves in a circular fashion. This illustration aims to show the dilemma of scientific design research: Objective outsiders are mystified while those subjectively involved understand.

Keywords. System boundaries; design; objectivity; subjectivity.

1. System boundaries, input, output, re-entry and difference

No man ever steps in the same river twice,
for it's not the same river and he's not the same man.
Heraclitus: On the Universe

Computer-aided architectural designing is an endeavour in which the boundaries of systems are crossed. "System" is understood here as whatever set of elements an observer considers to act together, following a common goal. An observer may choose to regard the components that make up a computer as a system. Similarly, an observer may choose to regard the organs making up the organism of a designer as a system, or consider the designer and the computer together as a system. With these different ways of looking (Weinberg 2001, pp. 51ff.), the imaginary boundary that circumscribes what is regarded as a system changes, and what is considered a system lies in the eyes of the observer.

Sometimes there are physical boundaries containing what is regarded as a system, such as the skin of a designer and the case of a computer – but this is coincidental. Designer and computer together may be regarded as one system contained by an imaginary, but without a physical boundary. Patterns in the widest sense crossing the imaginary boundaries of systems are, depending on perceived direction, called inputs and outputs. If the human is considered as a system, then making (the interior self affecting the exterior other) and learning (the exterior other affecting the interior self) constitute instances of outputs and inputs crossing boundaries. Illustrating the constraints of surprise and of observation in the context of such boundaries, this paper describes a simple technical system (a typography-generating system) which yields unpredictable output, provided its relatively simple inner workings remain hidden.

To justify this metaphor, it is necessary to acknowledge the human mind not as a static stimulus-response system, as a static translator between inputs and outputs, but as a system whose input channels are subjected to its own output. Contrary to the technologies it currently tends to develop, the human mind is subjected to what it itself produces and is thus changed by its own performance (see Figure 1).

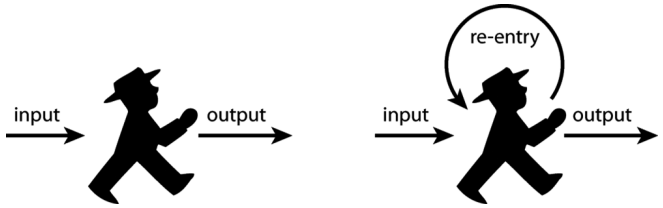

Figure 1. Human viewed as stimulus response system (left) and with the acknowledgement of human expressions re-entering as stimulations (right).

The loop which is thus formed allows expressions of the mind to re-enter into the mind where they may leave increasingly stable traces (Glanville 1997), i.e. memory. This view was substantiated in Von Foerster's (1950) interpretation of a previous study of human memory. In that previous study subjects had been asked to memorise random, meaningless syllables and to recount as many of them as they could afterwards at regular intervals. Memory and progressive forgetting were shown to follow an exponential decay curve, which did not approach zero, but a number of syllabi greater than zero that the subjects were increasingly more likely to remember permanently. Von Foerster explains this with the human being capable of both input (listening) and output (speaking), and hence circular closure and re-entry of articulations. Thus, every re-counting of a remembered syllable (output) is also a new

input which reinforces what is known. Repeated recalling thus leads to an eventually stable subset of remembered syllables. Von Foerster (2003) illustrated processes of this nature using his notion of the trivial machine, which he juxtaposed to his notion of the non-trivial machine. Both these models have an input and an output. The trivial machine predictably translates inputs into corresponding outputs, so that an external observer can, after a while of observation, establish a clear causal relationship between possible inputs and resulting outputs, for example in the form of a "truth table". A complete truth table is a reliable model for predicting the trivial machine's output response to a given input, irrespectively of how long the machine has been in operation. The non-trivial machine, in contrast, contains another input-output machine, with a feedback loop of its own generating internal states (labelled z in Figure 2) that affect the machine's behaviour and results in a vast number of possible outputs that cannot be reliably predicted by an external observer (Glanville 2003, p. 99). The non-trivial machine's operation, with changing internal states, can be said to leave traces in the machine through which the machine in effect turns into a different machine with every operation. An outside observer cannot easily establish a reliable truth table by which outputs resulting from given inputs can be predicted.

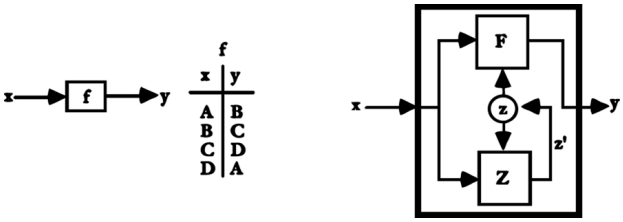

Figure 2. Trivial machine with truth table (left) and non-trivial machine (right), reproduced from Von Foerster (2003), 310–311.

The distinction between the trivial machine and the non-trivial machine deserves attention in general and in particular in our field because in every encounter the choice between both metaphors determines much of the ethical stance one takes – towards others, tools, buildings etc. Virtually all of our science and technology corresponds to the principle of the trivial machine in the sense that a given input is expected to always reliably lead to the same output. Multiple computers are, put simply, expected to always have the same response in the face of the same task or problem. Stereotypical engineers, managers and representatives of other professions, be they allied with architecture or not, are likewise expected to arrive at the same results when presented with

the same input. In the education of these professions this aspiration to the ideal of the trivial machine is enforced with the principle of scientific repeatability. Multiple stereotypical engineers tasked with the same structural analysis problem, or the same engineer tasked with the same structural analysis problem twice should reliably arrive at the same results, i.e. fulfil expectations predictably and reliably. Briefing multiple architectural designers with the same project brief, in contrast, makes sense only if variety amongst multiple responses is desired. Briefing the same architectural designer with the same task twice will also lead to two different outcomes because the second time around, one would be facing a different architect – one who was subjected to her/his own first design process and outcome, which left traces in her/him and thus changed her/him. In this sense, and in the sense of the above quote of Heraclitus, one cannot design (or learn, for that matter) the same thing twice.

2. Variety and automated production

Surprising variety (in the cybernetic sense: number of choices available) and reliable predictability are, paradoxically both for better and for worse, essential human needs and human characteristics (Fischer 2010, p. 611). We experience this paradox in numerous contexts in which we enjoy both stimulating variety in expression as well as economic and organisational benefits of uniformity. In shaping our products and environments, the advantages offered by predictably uniform (hence interchangeable) prefabricated components famously gave rise to assembly-line based production since the early days of industrial production; and it is part and parcel of architectural construction today. Having been introduced to architecture with uniform building elements, prefabrication brought along with it sameness at the scales of component repetition. At small scales of component repetition, such as that of clay bricks (Fischer 2007, p. 45), interchangeability may be appreciated for allowing flexibility and subtle texture. At larger scales such as that of floor plans or whole buildings as found in *Platenbau* developments (Hopf and Meier 2011), repetitive sameness is criticised for being monotonously boring or even socially detrimental. Aiming at repeatable input-output relationships, early computer applications in our field focused on predictable input-output relationships, leading to criticisms of applying the computer as a "fancy drawing board" (Dantas 2010, p. 161) and of valuing it as an equivalent to "an army of clerks" (Alexander 1965). In architecture and in other industries, there are now tendencies acting against monotonous sameness. Referred to as customisation approaches (Gilmore and Pine 1997), these tendencies are increasingly aided by computational (generative, parametric etc.) techniques that allow increasing of variety via circular feedback. The development of typography follows a similar pattern. Move-

able type introduced economic benefits along with monotonous sameness to book printing. Using type wheels and the like, typewriters, teletypes and computer printers achieved similar predictable sameness and cost-efficiency also in documents produced in small numbers. Contextual variations such as ligatures have been introduced to mechanical typesetting. Some contemporary computer typefaces go further and achieve "organic", "random" or "handwritten" appearances by introducing randomness to curve paths or by providing sets of alternative glyphs for the same characters.

3. Enigma cipher machine

While most technical devices – in particular digital ones (Fischer 2011) – are designed to function in the fashion of the trivial machine, there are a few that were designed to approximate the characteristics of the non-trivial machine. One of them is the Enigma cipher machine used by Nazi Germany before and during World War II. The machine is used to encrypt and to decrypt text messages by substituting letters with a replacement mechanism that changes systematically as the machine is used. It looks somewhat akin to a typewriter, with a qwertz keyboard (label 1 in Figure 3), but, located just above the keyboard, is a grid of alphabetically labelled lamps, also arranged in a qwertz layout (label 12 in Figure 3). Keys close electrical circuits that are routed into a sequence of 3 to 5 (depending on the model) exchangeable and rotatable cylinders (labelled 6, 7, 8, 9 in Figure 3), each with an "arbitrary" wiring between usually 26 inputs and 26 outputs (one per each key and lamp; see labels Fig. 1 and Fig. 2 in Figure3), then returned back through these cylinders and to the set of lamps.

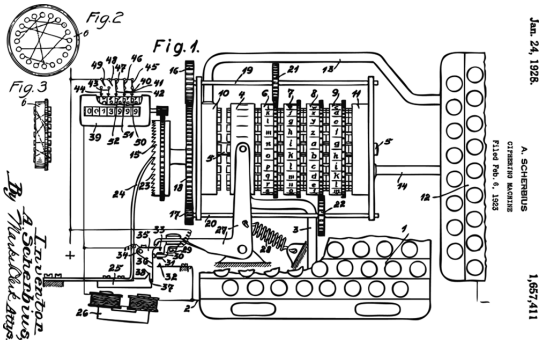

Figure 3. Schematic diagram of Enigma machine (from Scheribus 1928).

Pressing a key will activate one of the lamps, apparently at random, according to selection of cylinders and their current orientation. Additionally, each keystroke results in the rotation of the first cylinder by one of 26 rotation posi-

tions, after 26 keystrokes, the second cylinder will also rotate by one position and so forth, somewhat in the fashion of the digit cylinders in a mechanical odometer. Thus, each keystroke results in a new wiring between keyboard and lamps coming into effect for the subsequent keystroke. In other words: Use of the machine leaves a trace in it, changing the wiring of the machine, and hence the cipher, progressively. (Due to the symmetrical setup of the wiring going into the cylinders and back out through the same cylinders, the same machine setup can be used both to cipher and to decipher. The identical setup is achieved by referring to a secret timetable based code book of which both ends must hold a copy.) To an outside observer the input-to-output mapping of the Enigma machine is extremely difficult to determine, while it is perfectly determinable to those who developed it and who have a good understanding of its setup and inner workings. With inner workings of this kind the Enigma machine shares key characteristics of designing, making it a useful metaphor for the purpose of showing how designing is a relatively straight-forward process when viewed from the inside perspective but mysterious and wonderful when viewed from the outside perspective.

4. A typographical metaphor

The illustration presented here is a piece of software predicated on the Enigma machine and implemented as a VBA script controlling Rhino3D. Glyph renderings of characters input via keyboard are distorted dynamically and individually, with the use of a "private key" string stored inside the system. Somewhat akin to the (de)ciphering process of the Enigma machine, each key that is typed, modelled, transformed and rendered changes the internal state of the system (leaves a trace in it) to change the way the following glyph is distorted. In contrast to common computer typefaces, glyphs of same characters are unpredictably variant. As a point of departure, the system uses the typeface Helvetica to derive initial glyph outline curves for each typed character. The system then applies a combination of six Thompson (1992, pp. 1053-1090) transformations (see Figure 4) to these outline curves. Thompson transformations (parametric "warping" based on quadratic functions, Wilkinson 2005, pp. 223-224) as illustrated in Figure 3 above allow positive and negative transformations based on parameters P1 through P10. Of these, the presented generative system uses the six parameters P1, P2, P3, P6, P7 and P8. Parameters P4, P9 and P10 are ignored while P5 can be toggled manually, providing an "italics" option. Parametric input for the six Thompson transformations performed by the system is derived from the ASCII bit patterns of characters of a "private key" string, which is "rotated" by three characters with each input key stroke. Any ASCII string of any length can be used for this purpose.

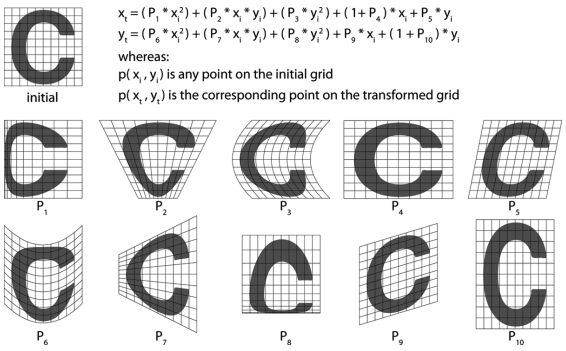

Figure 4. Quadratic functions and Thompson transformations based on parametric variation.

Once a key is pressed, the first three characters of the "private key" string are converted to their respective ASCII bit patterns and the six last bits of each are used to produce two factors out of the set {-4, -3, -2, -1, 1, 2, 3, 4}, which are multiplied with a scaling factor (0.075 gives a good effect) to produce a total of six parameters (see Figure 5).

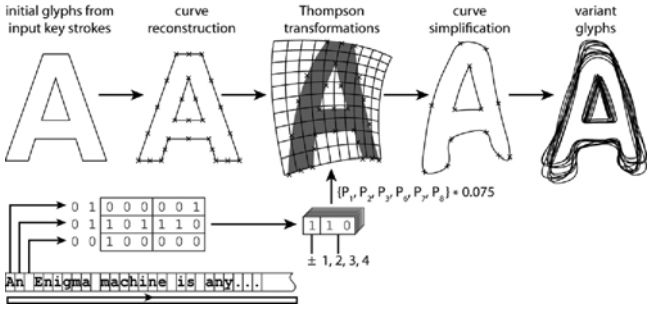

Figure 5. Key operations of glyph-variation based on "private key" string.

Following parametric Thompson transformations, the resulting glyph outline curves are simplified by reducing their numbers of control points, resulting in casual looking, "blobby" glyphs. These are variant with identical characters being shown as different glyphs (see the bottom line of Figure 6). Overall, the resulting types are nevertheless largely consistent and recognisable as members of the same typographical style, which I call Polymorph. The generative system includes a rudimentary automatic kerning function, the performance of which is also visible in the bottom line of Figure 6. The top line of Figure 6 shows the typeface Helvetica. The middle line shows the hand-

drawn, Helvetica-inspired typeface YWFT HLLVTKA Round, each character of which looks irregular, while identical characters are rendered with the same glyphs.

Figure 6. Helvetica (top), YWFT HLLVTKA Round (middle)and Polymorph (bottom).

Just as the Enigma machine's cipher output is enigmatic and unpredictable to outsiders such as wartime enemies, the glyph transformations generated by the described system are unlikely to be predictable to outsiders of the system. Nevertheless, both systems are perfectly determinable and appear straightforward to those aware of both systems' setups and of the ways in which the performances of both systems leave traces within them, changing their internal states, thus in effect leading to new inner workings with each operation. Designers, articulating and (re-)considering ideas can be seen as embodying a similar, non-trivial re-entry structure which, similarly, can appear either surprising and unpredictable or straight-forward and traceable depending on an observer's inside or outside perspective.

5. Observations

Some processes are linear, predictable and seem causal while others are circular and unpredictable. The difference can be shown with the distinction between the trivial machine and the non-trivial machine. Like the Enigma machine, instances of designing can be viewed as circular systems (Fischer 2010, Gänshirt 2011, p. 79) which display the structure and quality of the non-trivial machine. This principle can be implemented technically and used to generate design outcomes (Glanville 1992). Numerous examples have been presented in our field and the typography-transforming system presented here is another one. The wonder and surprise offered by such systems exists for as long as their interior workings evade observation (Fischer 2008). Design is, on the inside, concerned with what is unpredictable to outsiders. It hence corresponds to the non-trivial machine. Science, always on the outside, is concerned with prediction and hence corresponds to the trivial machine. This poses a challenge to scientific researchers aiming to research into designing objectively, somewhat comparable to the challenge of cryptography that leaves outsiders mystified while insiders understand. Design processes can be appreciated and understood on the subjective inside. Objective scientific description, though, is required to approach design from the outside.

It is difficult to view both from the inside and from the outside of the boundaries of a system one observes at the same time. Hence it is difficult to be mystified by what one understands (and vice versa), and to appreciate what one is not a part of (and vice versa). While this state of affairs has been pointed out for decades (Glanville 1982) it is not yet addressed sufficiently in our field. Postgraduate students whose work is scrutinised closely under both designerly and scientific criteria are particularly affected.

Glanville's (2003, pp. 98-99) view of the non-trivial machine goes beyond that of Von Foerster (2003, pp. 310-311), who originated it. Von Foerster on the one hand describes it as two trivial machines, one nested inside and changing the internal state of the other, resulting in unpredictable selections from a finite number of choices available (as the Enigma machine does). Glanville on the other hand does not explain the non-trivial machine's inner workings, for doing so would turn it into a trivial machine. Instead, Glanville grants the non-trivial machine the capability of increasing the number of choices available. This can be done, in principle, by differentiating fewer available choices into more available choices, or by charting uncharted territory to make new choices available there. Both views of the non-trivial machine describe processes that offer us wonder and surprise. Processes of both kinds suffer in the presence of scientific description: When hidden mechanisms making apparently random selections from given sets are revealed, their mystery is destroyed (an aesthetic loss). But worse: The capability of making more choices from fewer choices, where it still exists, is denied (an ethical loss).

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PROTOTYPICAL ARCHITECTURE

Design research method with full-scale models

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Abstract. This paper will discuss the role of the prototype in the design process, in the context of adaptive principles and iterative procedures. The starting point of this study will be the analysis of several recent projects from THEVERYMANY™ and their concept of "prototypical architecture". This paper aims to give an insight into both a different conception of architecture and the specific ways of research-oriented work which have redefined the role of the prototype in the design process. In the analysis presented here, the role of computer-aided architectural design is seen as fundamental in the development and further improvement of the iterative design process through faster and more affordable construction of prototypes.

Keywords. Prototype; prototypical architecture; iterative design process; full-scale model.

1. On exactitude in science

"In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast Map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography". (Borges 1946)

2. Prototypical architecture

Over the past few years, quest for The New has led architectural avant-garde to engage in relentless production of prototypes in the form of full-scale models made for the purpose of testing various ideas and processes. Obsession with the diagram, dominant over the previous architectural discourse is now replaced with a working method encompassing construction of models at their own scale. Costly as they are, often utilising a wide spectrum of computer-aided architectural design and manufacturing systems, these prototypes do not have utilitarian purpose; e.g. they do not necessarily provide shelter of any kind. The reason for constructing them also surpasses pure sensorial engagement. Their purpose is equally remote from the representational role of architectural maquette, and the need to transform the viewer's perception which is central to art installations. Nature of prototypical architecture is purely research-oriented; it is set to operate in the territory not yet visited by the contemporary architectural practice.

The term "prototypical architecture" comes from Marc Fornes (2011), who is using it to explain design and construction of projects which he produces in sequences. Under the pseudonym THEVERYMANY, he has been working in the field engaging both architecture and computation to explore new possibilities in morphologies, materials and assembly techniques. Many of such experimental projects are now built and provide valuable research material for this topic. His ideas are related between themselves, and their development may be observed through several continuous streams of investigation. Their sequential order provides evidence of the concept evolution and methodically documents building technique development. To provide an account of this assertion, I will look into four recent and completed projects of THEVERYMANY: n|Edg, n|Strip, Y/Surf/Struc and nonLin/Lin Pavilion.

2.1. Y/SURF/STRUC CASE STUDY

In 2011 Y/Surf/Struc, now part of the permanent collection of the Centre Pompidou, was conceived as an experiment with a self supporting surface morphology whereby structural members are opening up and lending themselves to a surface condition. Its geometric logic explained by the author is a combination of two distinct systems, distributed and hierarchical, resulting with what is referred to as 'Y' model (Fornes 2011). Entire surface is made of tripartite segments tapping into each other and making it very difficult for the eye to distinguish between the part and the whole. Initial modeling is done in relation to immediate surroundings and in regards to the structural considerations of the most suitable supporting points in the given environment. Secondly, surface

curvature is controlled and amended to allow for more optimal materialisation. Both conception and fabrication of such model are heavily dependent of computational protocols as surface is being continually reconstructed in the process of search for the most viable solution. Surface geometry is understood and described through a large number of referential points whose densities are relative to the degree of curvature. Greater surface curvature results with more points and consequently finer tessellation will results with more parts in the fabrication process. In the end, surface is converted into a number of developable elements which can be unrolled and cut out of flat sheet material, in this case aluminum.

2.2. N|EDG AND N|STRIP CASE STUDY

Figure 1. N|STRIP by THEVERYMANY.

The understanding of the surface morphology through custom computation and digital fabrication has been central in THEVERYMANY work for number of years. The method requires intricate work on the intersection of several disciplines. In 2009 n|Edg model has tested a novel procedure in describing complex surfaces with flat components by replacing standard triangular elements with polygonal ones defined by n number of edges. When put to work, such solution with lesser number of parts and joints resulted with quicker and easier assembly process. Consequently, in 2010 n|Strip model was driven with the similar idea of economising on the number of components. It employed a protocol to reconstruct a surface with a smaller number of developable elements, this time organised as linear stripes (Fornes 2010). In result, the construct was assembled much faster. Both n|Edg and n|Strip projects have already showcased aspects of the Y model geometry and have been important milestones in its development, both providing knowledge necessary for its construction. In the meantime THEVERYMANY has carried out other related

experiments, using different materials and tessellation techniques which have yearend valuable information but have not lived to the same expectations. For instance, construct of walnut veneer, made for the Union Square in New York, collapsed under its own weight before reaching its destination.

2.3. NONLIN/LIN PAVILION CASE STUDY

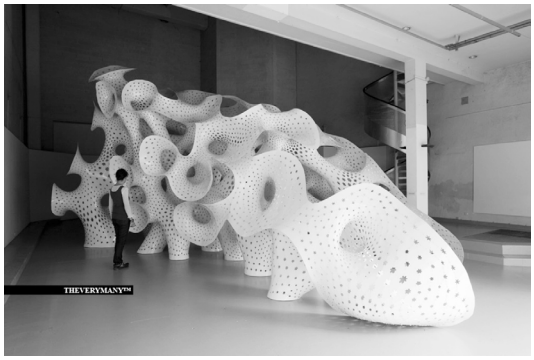

Figure 2. NONLIN/LIN PAVILION by THEVERYMANY. Photo Francois Lauginie.

Finally in 2011, nonLin/Lin Pavilion, now part of the permanent collection of the FRAC Centre in Orleans, once again synthesises experiences acquired in the previous experiments and uses surface paradigm to generate spatial environment. Here too, understanding of the complex surface morphology is essential to the design process. Reusing the knowledge acquired in the previous iterations of the Y model idea includes techniques used for representing surface as information that can be translated and materialised into a series of planar stripes ready to be cut out of the flat aluminium sheets. Yet, there is no universal procedure to resolve every tessellation problem. Instead of the global application strategy of populating discreet components onto an overall host, the approach relies on the coordinate use of multiple and simultaneous codes (Fornes 2011). In other words, overall surface model goes through the process of recombination. It is continuously divided and then put back together, altering between the states of subdivision and union, until satisfactory solution has been met. State of subdivision allows for the multitude of specificities to be dealt with differently and in accordance with local conditions. State of the union provides for synchronisation of otherwise dipartite segments. The author describes the Pavilion as a "non-linear structure" (Fornes 2011), alluding to the morphological condition of change, similarly to what is used in the science of physical cosmology to explain formation of large scale structures.

2.4. CASE STUDY CONCLUSION

In conclusion to this case study analysis, the concept of "prototypical architecture", as used in this paper, establishes profoundly different conception of architecture and specific ways of research-oriented work which has redefined the role of the prototype in the design process. To provide better understanding of the term, further analysis is presented in four segments which form the core chapters of this paper: prototyping research method; iterative design process; reference to known prototyping practice in architecture; and future role of computer-aided architectural design and manufacturing in prototyping-based research

3. Prototyping research method

Prototyping is one of the recognised study and research methods in design-related disciplines, and in this context it belongs to a specific way of modelling, not to be confused with making of architectural maquettes. The purpose of scientific models is to represent reality. In order to be able to inform, communicate and reflect on reality we must imagine, articulate and simulate within a model (Klaasen 2005). In this sense models may be made of words and numbers, and need not be necessarily spatial as often understood by architects. There are different models in use and there could be a basic distinction between two different kinds: predictive and descriptive. Prototyping is unique in that aspect, as it includes both ex ante evaluation or prediction and ex post evaluation or description (Van der Voordt 2005). After construction, *ex post* research of the prototype may give rise to improvements and *ex ante* research that may lead to design adaptations or to the conclusion that design is ready to be built. Full cycle of study thus consists of building, testing and reformulating the design. The process may be of sequential order, with any number of such cycles. Also, design alternatives may be tested simultaneously and relation between *ex ante* and *ex post* evaluation may become less apparent.

4. Prototype in the iterative design process

Purpose of any prototype is to acquire knowledge which will be solely used for the construction of the subsequent model in the chain of iterations. Prototypical design process will repeat itself in an iterative fashion through several generations until the optimal solution is met. Instead of one and finite solution to the design problem, iteration sequence is a process of adaptation with a visible structure. This approach can be deployed in various disciplines: for example, iterative development is also a form of software development methodology: it starts with an initial planning and ends with deployment with the cyclic interactions inbetween (Larman and Basili 2003).

In architectural realm, the idea may be traced back to sixties and Christopher Alexander's research into the analytical nature of the design process which he contrasted with pure intuition and willful form making (Alexander 1964). His assertion was that design process for its complexity needs a certain structure whereby architectural form undergoes course of "gradual adaptation". Christopher Alexander's thesis was published in the book "Notes on the Synthesis of Form" (1964), in which an inspiring parallel between the process of biological adaptation and the process of design was drawn. He was interested in the relation between the form and its physical context and was an early design theorist to point out toward the work of Scottish zoologist, D'Arcy Thompson (1959) who at the turn of the century has explained changing anatomies of living organism under the influence of environmental forces. His remark that equaled form to a diagram of forces is heavily quoted by architects till today. When translated to architectural terms, this biological paradigm offered a fertile ground for new ideas on spatial form. In design world, Thompson's study "On Growth and Form" connected to the idea of the changing form and its multiple iterations according to appropriate performance related criteria such as construction method or use pattern.

Consequently and with the advance of computer-aided architectural design systems a specific ways of working in design oriented practices started to emerge, encompassing production of series of solutions prior to committing to the ultimate one. Today, a number of software packages deliver ready-made solutions for iterative design procedures via parametric control of geometric constructs with interrelated entities. A designer can more easily produce a number of digital simulations, each to be evaluated under specific criteria and in turn provide information for the next and more developed version of the design. Other designers develop custom tools reliant on scripting techniques and use of computer languages to establish and control iterative structure of the design processes. In both cases, greater investment is needed at the outset of such design process, with time and skill required to write a code or set parametric connections between the elements of the geometric model.

The economy of iterative concept is simple. After initial investment, design process may take iterative discourse to exploit certain idea development through a series of models along the continuous line of investigation. Benefits rest in more robust results, better development of the idea and more comprehension of the initial design problem. More trials there are the better will be the result. It is a methodological shift from one to many; from a single form to a series of forms each developed with its own specificities but also related to the one preceding its development. However there is nothing to suggest that standardisation and repetition are obligatory consequence of iter-

ative development. It would be more correct to conclude that throughout iterative development only key aspects of architectural form stay constant, while others evolve to fit different needs.

This way, a designer anticipates development of the original idea through series of leaps which all generate data to foster the advance of the design. Such information may not be obvious and may make profound and unexpected turn in the design process. Moreover, it may help develop solutions dependant on testing as they may not belong to any known architectural typology. Iterative design sequence contains generative capacity. It is a way in which architecture can change to develop new and more agile ways of working to produce spatial organisations in response to changes taking place in new forms of social, cultural and economic institutions. Transparency of the iterative design process opens up the possibility of interdisciplinary and participatory development of the design process itself, allowing professionals from different fields and even end-users to take part in the decision-making process.

5. Prototyping practice in architecture

The idea of a prototype is not a new one. In industrial design, prototyping is a very common way of product development through testing of alternatives solutions. Prototypes are evaluated according to certain performance aspects or used to gain information from their interaction with users. Sometimes they serve the sole purpose of advertisement. In architecture too prototyping has been known for some time but in-spite of its obvious usefulness, it has been scarcely used. Predominantly, it is employed for the design of buildings which will be produced in large series of possibly identical structures, and will be able to justify initial investment in the construction of prototypical projects. This concept is literally borrowed from the industrial design, where the idea of the prototype originates from, and where it is more common to produce items in large series.

Van der Voordt (2005) makes note of several initiatives taken in 60s in the US and Netherlands to test and improve design for healthcare and correctional facilities. In all cases actual variants of buildings with different layouts were erected and then investigated according to occupancy scenarios, efficiency, running costs, energy consumption, safety and subjective perceptions of its users. Variant solutions were compared to one another in terms of the cost and quality. In addition to observation and measurement of quantifiable information, post occupancy evaluation included a set of questionnaires completed by several hundreds of staff members. Together this has provided data based evidence to be used for the development of the new model. In the long term, such study may suggest more initial investment that can be gained back in

number of years or it may result in knowledge that can be directly applied to more economic construction of a number of following projects.

More often it is not feasible to build for the purpose of testing. While in industrial design prototypes are often made in real-scale and with the use of the actual materials, in architecture this is harder as building projects are significantly bigger and more complex. Therefore concept of prototyping if often downgraded to more viable ways of working. Change of scale could be the most obvious compromise to be made, but it would also bring the idea closer to the role of a large maquette that could provide only limited findings about spatial organisation or materialisation. Another plausible solution is to build a segment of the overall design on-site as a mock-up test to investigate behaviour of unconventional building materials or examine technical solutions such as facade joints. Nevertheless, mock-up tests do not generate other valuable information concerning overall structure. Similarly, construction of buildings with large number of similar of identical units, such as housing projects or hotels, occasionally include production of one such unit in real scale prior to the construction of the project for no other purpose but to act as advertisement showcase. All of the above named solutions provide only partial answers. While their value is not questionable, their purpose is directed toward certain aspects of architectural project and their correspondence to entire architectural undertaking is never absolute. Fidelity of any representational model is proportional to the quality of information generated through its testing and thus directly related to its purpose in the design process.

6. Future role of computer-aided architectural design in prototyping-based research

In contrast to previously described use of prototyping within architectural practice, this paper identifies another emerging area within the same field, based upon production of self-sufficient and autonomous prototypes, made without scale and with no utilitarian reason. Their purpose is to gain knowledge, to help develop architectural ideas and to put to test "re-emerging relationship between architecture and construction" (Kolarevic 2008, p. 151). Prototypes are highly unique when compared to the other architectural tools, such as digital models, maquettes or drawings. They are the only instrument in the hands of the architects that deals directly with questions of materiality. Prototyping exercise involves fabrication choices and construction strategies in parallel with the formation of the design intent, thus prompting unified thinking about conceptual and material aspects of the design process.

On one side prototypes are instrumental to exploring possibilities of current digital processes and their prospects with the role in establishing new design

procedures and fabrication techniques. On the other hand, they are highly dependent on the development of computer-aided architectural design and manufacturing systems. For some time now, the potentials of current digital tools hold a key to more efficient structure of the design process. The demanding nature of iterative development and prototyping seeks investment of both time and finance, and its future is dependent on the development of more economic ways of working.

Computer-aided architectural design systems and building information modelling solutions are supporting a growing tendency to substitute physical prototypes with more effective digital simulations as modelling techniques are developing precision and more importantly the ability to capture material properties along with the geometric ones. In automotive industry, simulation models are already deeply integrated into the iterative process of prototypical development. In the well known case of the Boeing 787 Dreamliner, the first full-sized physical realisation was made on the series production line. In architecture, this is more difficult for a number of reasons. One of them is related to the link between computer-aided architectural design and manufacturing systems that is still much more developed in automotive industry. Arguably the easiest and the quickest route from digital to material in architecture is via "rapid prototyping" solutions, most often based on additive manufacturing technique whereby form is created from a great number of very thin layers of material. Also known as 3D printing, this process offers almost instant solution for an early insight into the physical form. However, very often it has little to do with actual fabrication process and might be even misleading to the actual design intent. Preparations for 3D printing have very little in common with actual fabrication strategy regardless of the fact that it will produce a true physical representation. Moreover, capabilities of the rapid prototyping machine will limit the choice of materials and design options. In that context both digital simulations and 3D printing present important aid in iterative design process but cannot be taken as the replacement for actual construction of prototypes.

In conclusion, the role of computer-aided architectural design is seen as fundamental in the development and further improvement of the iterative design process through faster and more affordable construction of prototypes. Introductory analysis of THEVERYMANY works presented here, show an example of architect's engagement with both design and building process, and the establishment of a new form of research oriented practice based on the production of prototypes. The challenge we can identify here is in further integration between digital processes of design and fabrication, along with the creative combination of digital and analogue modes of working. Here we spec-

ulate that the "prototypical architecture" is the right testing polygon for this. Having analysed the theoretical approach in this paper, further research will involve practical case-studies of the applications of the prototype-based iterative architectural design process. Finally, in direct relation to CAADRIA2012 sub-title, the work described here suggests that the route from "bricks and mortar" to "nuts and bolts" and on to "codes and pixels" could unfold in a non-linear fashion and active interchange between digital and physical domains.

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DIGITAL CONCEPTION(S)

Architectural concepts of digital design and making

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Abstract. This paper presents an investigation of probative works of architectural thought and production executed in various forms of digital design and computational media. The applied design research focuses on an examination of the procedure or process constructed to both develop exact, precise digital models and constructed processes that result in design outcomes that cannot be pre-visioned. The changing position of the conceptualisation within the design process continually changes the relationship of the digital work and the computational framework. The work challenges one to interpret design processes of translation and transformation, through the continual oscillation between developed in pursuit of known results and constructed methods for making, in an effort to unravel the pretext of the singular point of view to reveal the intention of the design conception(s). The projects discussed here focus on relationships between the projection of space in architectural representation and the production of architectural form through complex geometries relative to discontinuities and the way in which they agitate and alter one another. DIGITAL conception(s) operate across three primary areas of research; animation, conceptualisation and fabrication. The work oscillates between digital and physical artefacts that intertwine digital/physical workflows while simultaneously engaging temporal issues of time based media through motion graphics and animate constructs.

Keywords. Design representation; visualisation; design theory.

1. Introduction

Digital craft engages both issues of design representation and design process. The DIGITAL conception(s) research conducted focused on probative works

of architectural thought and production executed in various forms of digital design and computational media. This applied design research was conducted by undergraduate and graduate students of architecture in and beyond my advanced computer applications in architecture seminar and aesthetics|media|politics studio over the past several years. The ideas and conversations that began in the seminar and studio have developed to broad reaching collateral effects (academic papers, design awards, prizes and honours) beyond their modest beginnings. The ideas and concepts promoted and interrogated throughout the projects are designed to develop and hone critical design thinking skills in the pursuit of multiplicitous conception(s) of architecture.

The works represent an ongoing dialog between the students, and myself, but more importantly they are the manifestation of meaningful interaction between the students and their ideas. The interaction of the two, moving in seemingly unorthodox ways to test and probe the digital design concepts and digital media techniques, allow for a deeper comprehension of architectural space and form. DIGITAL conception(s) operate across three primary areas of research; animation, conceptualisation and fabrication. The work oscillates between digital and physical artefacts that intertwine digital/physical workflows while simultaneously engaging temporal issues of time based media through motion graphics and animate constructs. The boundaries and interpenetrations between the areas of work are frequently blurred, as the conceptualisation of architecture is often a messy business.

The most common preconception related to this work is that digital design processes, forms and aesthetics are free from a historical context or value system. In DIGITAL conception(s) the opposite is true. In fact, most of the digital processes and techniques explored here are intimately linked through a deep and long-standing tradition in architecture to seek clarity of architectural thought through artistic and scientific examinations of the theories, ideas and concepts that drive one's architectural preoccupations. According to Le Corbusier it was the modular, mathematics and purist painting that were the empirical research that drove his architecture. His research practice entailed the pursuit of both the computational and expressive sides of his mind simultaneous with his architecture.

Through the work in this research, students have found themselves emancipated from the narrow definitions of common preconceptions and misconceptions of digital design media. This work demonstrates many re-conceptions of the medium and the architectural design process. The projects are driven by an interest in developing a range of design solutions rather than fixating on the pursuit of a singular solution to a given design problem, privileging process over product. The projects have introduced the students to the ability to

manipulate information and computational systems as design tools that operate within the design and conceptualisation of architecture. The task is to develop a thorough understanding of how changes in design technologies, such as animation parametric modelling, scripting, and digital fabrication serve to provoke a reinterpretation of the design of architectural form and space.

The tradition(s) of exposing architectural ideas through the rigorous research of recombinant geometries, narrative systems, and the art and craft of making are deeply held value systems that bind this work. Through the immersive engagement of the tools, techniques and processes of digital media, several misconceptions are revealed, repaired and removed. The challenge is to understand the opportunities presented when digitally driven design, process and production technologies are envisaged more comprehensively than as mere tools to fully embrace them as ways of thinking in and of themselves.

Through this ongoing work I am constantly challenged to facilitate re-conceptions in the evolution of the students and myself. This collaborative enterprise is imbued throughout my teaching, research and creative practices that are affected and emboldened by students' creative discoveries, technical obstacles and breakthrough moments.

2. Animation – spatial/temporal sequences

In the essay, Body Matters, Greg Lynn discusses the changing attitudes towards the geometric description of the human body and the corporeal metaphor in architecture (Lynn 1998). He proposes that our historical use of geometric descriptions of the ideal human form as an architectural language is lacking a relationship to our reality because they lack specificity and definition of bodies in time or space. If the body is conceived not just in space but also in time than the ability to reinterpret the body and its dynamic motion as the corporeal metaphor, engaged not as a static condition, but as a dynamic event. Abstraction and mathematical manipulations of proportion and scale are means to project boundaries through derived lines of profile and contour. The intention of this phase of the project is to develop a broader understanding of line by studying the relationship between profile and contour as both analytic and generative operations that must undergo a subsequent transformation to be realised as architecture. The assignment is to examine the relationship between human scale and metaphysical simultaneity, examining the ways in which ambiguities can provide organisational models for design.

Lines can be produced simultaneously as profile and contour through displacements of the point of view as degrees of intensity located along the continuity of space/time. In this study, we will develop an understanding of the potential relationships between the human body and architecture, a physical

metaphor of architectural assembly and as an experiential phenomenon of the living/perceiving body in space. This relationship demands of us the recognition of the necessary alignment or resonance between architecture's physical and mental constructs.

Animation is an extensive matrix of physical, spatial, visual and temporal forces. Animation is not just a process to be executed, rather an opportunity to derive and communicate meaning through the re-presentation of still images in a constructed sequence to imply or simulate motion. Animation and a cinematic approach to analysis of space and form through time can have a significant role in the generation of architecture and architectural inquiry and as such, has a significant role in the structuring of the architectural design process.

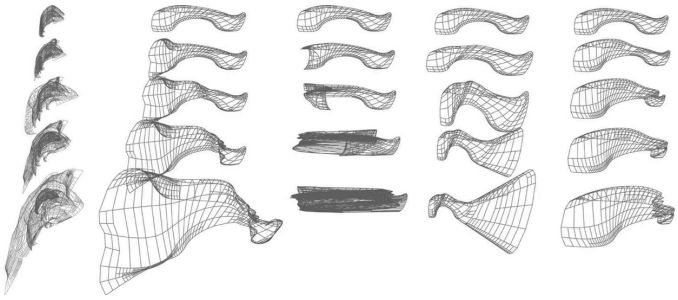

Figure 1. Studies of animate form (student work: Andrew Lindberg).

Animation is a process of projection, evaluation and ultimately speculation. Animation is a virtual approximation of the real, it is an illusion of motion virtually projected through the sequential re-presentation of the many as a singular motion graphic. Animation and the spatial/temporal modelling of a cinematic construct is a synthetic description of space-time that simultaneously engages techniques of analysis and re-presentation. This group project will employ two modes of investigation to develop an interpretation, a virtual projection of time and space, surface and depth. Animation and modelling as act, process, and product serve as the modes of investigation. The first animated flipbooks and films were created at the turn of the19th century. The fundamental principle and techniques of animation today were derived in the early part of the 20th century and perfected in the hand-drawn cartoon animations of the 1930's. In animation the illusion of movement is achieved by the rapid re-presentation of many still images in sequence. At the core of all animation is the principle that a sequence of still images re-presented through time can communicate a singular simultaneous view of the multiplicity of the images. From the earliest cell animations to the latest CGI effects all animation depends

on the composition of the still image in time. The spatial consequences of this means of representation are shown in Figure 1. In this example, a singular geometric construct is interrogated through a series of animated transformation. The geometry is transformed with each subsequent animate series. The work results in a matrix analysis of each developed sequence of translation.

3. Conceptualisation – rigorous geometries

> *"To disclose appropriate alternatives to the ideological stagnation plaguing most architectural creation at the end of the second millennium, the first crucial step is to acknowledge that the value-laden tools of representation underlie the conception and realization of architecture."*
>
> – Alberto Pérez-Gómez,
> *Architectural Representation and the Perspective Hinge* (1997)

Digital design technologies such as CAD, BIM, parametric, generative modelling applications, and fabrication are not tools, but instead propose ways of thinking, conceptual positions, to frame the work conducted in these media processes. This project will focus on a relationship between the projection of space in architectural representation and the production of space through complex geometries relative to temporal discontinuities and the way in which they agitate and alter one another. The motive is to bring about conflicts, identify problems to solve and to resolve the resultant disconnect in such a way that it brings about unanticipated forms, temporal experiences and patterns of spatial inhabitation and formal production. The example given in Figure 2 demonstrates the conceptualisation and development of a range of rigorous geometries. Each element in this study constitutes a singular event or configuration complete in itself, but forming part of the larger collection. It is the referential condition, the delta between, which is modelled and transformed to suggest various and multiple geometric definitions with respect to the formal and spatial portrayal through the composition of time, light, shadow and the conceptual framework. The capacity to represent or re-present spatial compositions is a unique skill and a primary task of the architect.

The function of architectural representation goes beyond the description of existing or future buildings to the conceptual and literal communication of meaning and intent. While most conventions of architectural representation and communication have implicit limitations in their capacity to represent architectural space, many reveal some of architecture's latent possibilities. Digital representation, with its own set of limitations, has the potential to liberate and provoke possibilities in architectural design and representa-

tion simultaneously by configuring new representational conventions. One of these is the prospect of animate, spatial description. Another is time and the fracture of spatial sequence through temporal isolation. All modes of architectural representation, however limiting and/or revealing, are as essential in the creative process of architectural design, as they are necessary in the production of building. Implicit in an architect's ability to project spatial and formal compositions, is the capacity to describe them by challenging representational conventions and other architectural forms of representation. In this sense, the work of the architect could be defined as the task of anticipation of space in time through the construction of representation.

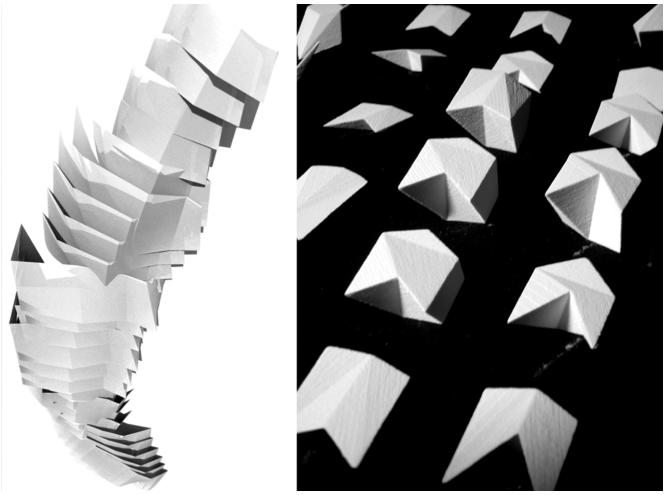

Figure 2. Translation of geometries (student work: Jonathan Healey).

The sectional implications of the cinematic or animate models recompile the analytic in a synthetic fashion. The proportions, scales, volumes and figural organisations found within the constructs generated suggest potential interpretations of spatial/temporal organisations and descriptive systems that project surface/depth. The work seeks to analyse and interpret the visual artefacts created through a series of images (2D & 3D & 4D) that investigate the organisational systems and hierarchies of the work in question. The goal is to reveal the ideas of scale and proportion embedded in the work through a series of sectional images that seek to describe the architectural (spatial) significance or potential of the forms. All attempts are made to expose the spatial implications inherent in the work. The intention is to dissect the work into its constituent parts then recombine them through a synthetic act to re-design an abstract interpretation of the collective understanding of the whole.

4. Fabrication – digital/physical workflows

> *"...witness extraordinary spatial and formal manipulations clad in metal panels that are rendered indifferent to the very geometries and spatial constructs to which they are meant to correspond. ...[attempt] to overturn this dichotomy and to create a condition whereby surface and space are understood as organically linked, with geometry and patterning as the agencies for their precise resolution."*
>
> –Monica Ponce de Leon & Nader Tehrani, *Versioning* (1995)

To develop a broader understanding of digital fabrication, as a means of conception the challenge is to understand the opportunities presented when digitally driven design, process and production technologies are envisaged more comprehensively than as mere tools (Kolarevic 2003) to fully embrace them as ways of thinking in and of themselves. One of the dilemmas of tool thinking is that it undermines the additive value of skills and intentions working together when conceptualised as a working methodology with its own rules and boundaries to be played within and against. A tool, such as a chisel, provides one way to remove material. As a tool of removal, a chisel is limiting. Digital fabrication is not a tool, but a way of thinking, a conceptual position that frames the way one operates within architectural design. Digital fabrication is not the chisel, not a tool, but, more precisely, it is the concept of removal that the chisel represents. Understanding and positioning fabrication as an engaged process or method of design and a way of thinking is far more powerful than limiting it as a tool. Understood as a progressive process of reiterative learning it can be developed and dissected into and throughout a curricular structure. Students must understand not only the model geometry but also the implications of the ways the model is constructed and conceived to develop a rigorous process of critical evaluation to understand the elements not only through convention but also design intent. Moving beyond tool thinking to that of a method, we can study the relationship between digital and physical workflows as both analytic and generative operations that must undergo a subsequent transformation to be realised as architecture. The assignment is to examine the relationship between the digital and the physical, examining the ways in which ambiguities can provide organisational models for design. The geometric development of physical artefacts can be seen as a process of description, communication and ultimately speculation. Void can be seen as the absence of description and communication that ultimately begs interpretation.

The intent is to conjure a reading of both the experiential, felt presence of motion and an external condition, which consequently destabilises the singular vantage points of the original referents. The hybrid images/animations

utilise hand drawing, modelling, photography, scanning and digital transformations to explore serial composition, repetition and/or extension. Figure 3 is an example of the physical construct that goes beyond the digital conception of its fabrication. Each layer of the laser cut acrylic model is etched and cut from both sides of one-inch thick Plexiglas. The literal and phenomenal transparencies developed in this artefact produced an emergent morphology of line, shape, structure and depth. The examination of the procedure or process constructed by the computational design process should be understood as the connection or relationship of several components in a particular sequence to tell a story of form, space and time. An action is choreographed through/against a context which conceptually reveals the space, and registers movement through time.

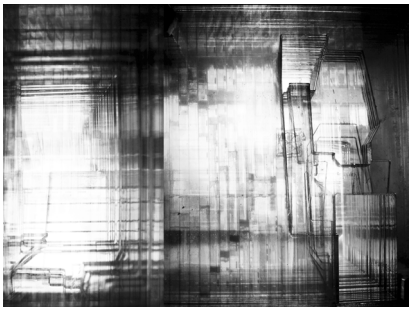

Figure 3. Morphological Sequence Study (student work: Jimena Amaral).

5. (Dis)assembly

> *"Contemporary techniques thus constitute the beginning, and the end, of the loop, which is perpetuated and proliferated by technology. This proliferation is contingent on an understanding of technology activated within its cultural context. The interaction between technology and the user creates the possibility for qualitative cultural transformation through the transmission of behaviors that are replicated."*
>
> –Ali Rahim, *Contemporary Techniques in Architecture* (1995)

Sectioning space and time to reveal analytic and synthetic relationships found in the modelling and representation is the objective of this phase of the project. The animated path around, in and through the model may be broken down into constituent parts and re-complied through spliced animation and/or it can be temporally sectioned and revealed through the motion of the view point through time and space.

The objective is to simultaneously express time and space an analytic/syn-

thetic engagement of surface and depth. Create an animation of a model that demonstrates a thorough investigation of surface and depth expressed through sectional understandings of the modelling construct. The animation should endeavour to re-present the spatiality of the constructed geometry represented through motion. Spatial relationships found within the form itself and in the process of its representation are fundamental to the exploration both as an analytic device and synthetic technique. Use of spatial motion and temporal displacement of the modelled surface are encouraged to re-present the model in a meaningful way. The constructed morphology results in a surface study that of a new recombinant sequence(s) constructing the space and time of the previous interpretation.

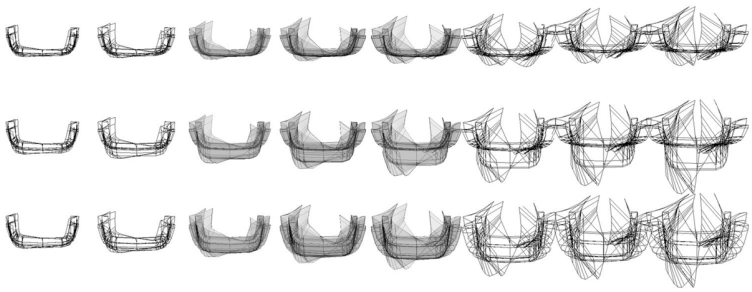

Figure 4. Known/unknown process study (student work: Christine Arnold).

This project focuses on the production of a physical spatial object/surface that is the morphological extension of the procedural operations. Time and space through motion and image are interconnected in both film and architecture. Sequence and didactic systems of representation are fundamental to both areas of design research. This project asks the student to consider how a sequence might be taken apart and recompiled in a new way that is critical and creative with the *assemble-deconstruct-reassemble* workflow.

6. Conclusion

The project discussed here focuses on a relationship between the projection of space in architectural representation and the production of space through complex geometries relative to temporal discontinuities and the way in which they agitate and alter one another. The projects are driven by an interest in developing a range of design solutions rather than fixating on the pursuit of a singular solution to a given design problem, privileging process over product. The projects have introduced the students to the ability to manipulate informa-

tion and computational systems as design tools that operate within the design and conceptualisation of architecture. The task is to develop a thorough understanding of how changes in design technologies, such as animation, parametrics, scripting, and digital fabrication serve to provoke a reinterpretation of the design of architectural form and space.

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