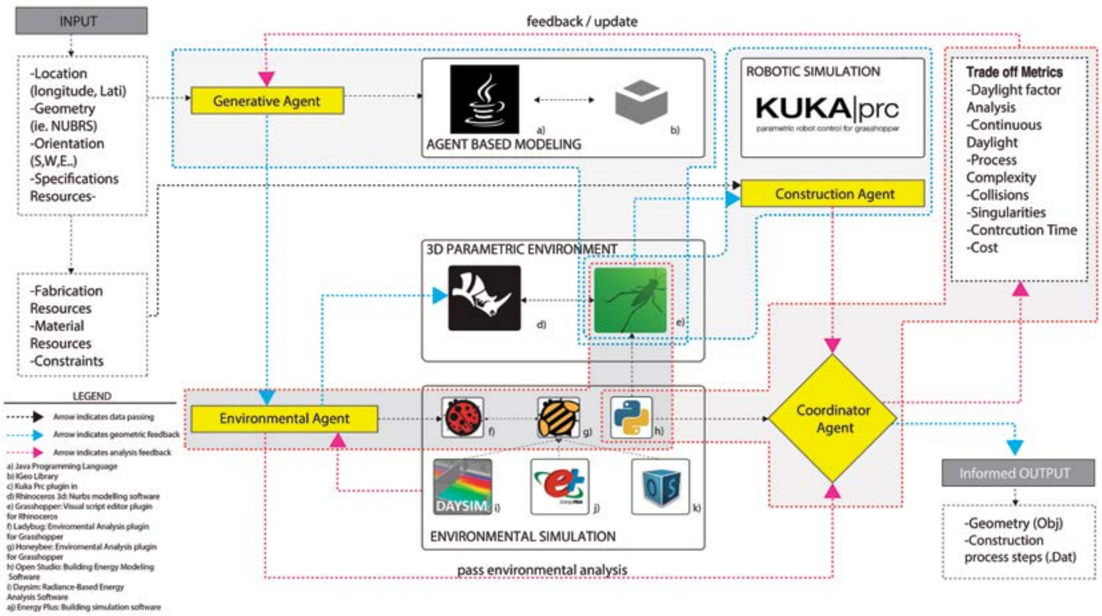
A Multi-Agent System for Facade Design

David Jason Gerber
Evangelos Pantazis
University of Southern California

A design methodology for Design Exploration, Analysis and Simulated Robotic Fabrication



1 Diagram illustrating all the components of the Multi-Agent Systems for Design framework and prototype. The diagram shows the sequence and data flow, system component interactions and dependencies, the agents, and feedback types and loops.

ABSTRACT

For contemporary design practices, there still remains a disconnect between design tools used for early stage design exploration and performance analysis, and those used for fabrication and construction of complex tectonic architectural systems. The research brings forward downstream fabrication constraints into the up-stream design exploration and design decision making. This paper addresses the issues of developing an integrated digital design work-flow and details a research framework for the incorporation of environmental performance into a robotic fabrication for early stage design exploration and generation of intricate and complex alternative façade designs.

The method allows the user to import a design surface, define design parameters, set a number of environmental performance objectives, and then simulate and select a robotic construction strategy. Based on these inputs, design alternatives are generated and evaluated in terms of their performance criteria in consideration of their robotically simulated constructability. In order to validate the proposed framework, an experimental case study of office building façade designs that are generatively created from a multi-agent system for design methodology is design explored and evaluated. Initial results define a heuristic function for improving simulated robotic constructability and illustrate the functionality of our prototype. Project limitations and future research steps are then discussed.

INTRODUCTION

The Rise of the Robots in Architecture

The rapid evolution of digital design methodologies and technologies in the Architecture Engineering Construction (AEC) industry, and its coupling with new fabrication and construction technologies, have provided architects with opportunities to move away from Fordist standardization towards a post-Fordist realm of previously unattainable design possibilities. While symmetry and repetition brought about economical efficiencies for the AEC industry, these norms are now becoming antiquated and surpassed by an era of digital design, analysis, and fabrication. Parametric design and its evolution into Building Information

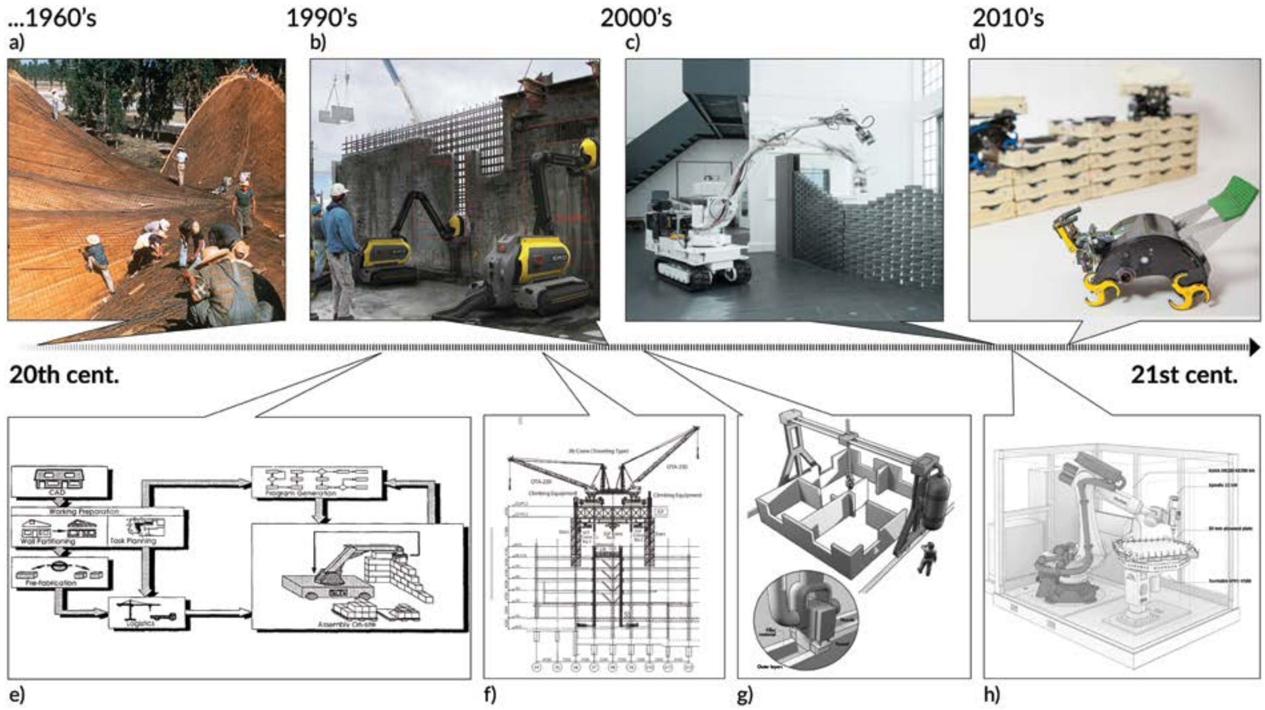
Modeling (BIM) has more efficiently facilitated the design exploration of new forms and multiple design alternatives for a broad spectrum of pre- and post-rationalization design approaches (Gerber 2012). Furthermore, simulations assist designers in making more informed design decisions by providing for higher degrees of certainty in the complex and synthetic design decision-making process (Roudsari, Pak, and Smith 2014).

While expert domains relied on the asynchronous handover of drawings, current practices seek the intelligent and rapid integration of environmental and structural analyses during the design exploration and development phases. By integrating these historically disparate and highly coupled architectural, engineering, and construction domains, the use of parametric models that accommodate design changes efficiently are now used to enhance environmentally conscious and cost-effective design solutions. With the explosion of new design technologies, there has also been an increase in the integration of novel digital fabrication techniques and industrial robots in architecture. These novel fabrication technologies have enabled the realization of complex geometric forms, and more generally, a paradigm shift towards mass customization, post-Fordism, and the non-standard (Racine et al. 2003).

Core to our research agenda is to continue to prove the importance of the architectural non-standard, and to use its intricacy and differentiation as an opportunity to not only provide higher performing design solutions in a multi-objective empirical fashion, but equally for the qualitative metrics of aesthetics and the communication of delight. In that regard, robotic fabrication offers a unique opportunity to reconsider the architectural design process as not just designing the building form to be constructed, but as designing the construction process itself, which equally infers a manifesting of its own aesthetic and inherent post-Fordist performance gains (Gramazio and Kohler 2008). The rapid integration of advanced digital and robotic simulation has led to the reconsideration of the architect as both a contemporary master-builder and a digital toolmaker (Tamke and Thomsen 2009). This further highlights the need for more integrated approaches for the AEC industry, and an urgency to develop new design methodologies that support a more holistic approach towards the adoption of robotics, not just as tools, but as participants in the multi-objective, complex, and highly synthetic design decision-making process.

Despite the numerous advancements, there remains a gap in intuitive workflows for designers to incorporate simulation results as drivers and constraints early in the design process (Kilian 2006). In addition, disparate software is used for different design phases—design generation, simulation, manufacturing, and construction planning—and consequently continuous information exchange among the AEC disciplines still remains a challenge (Scheurer 2007; Schwinn and Menges 2015). Most critically, current design methods and computational tools remain limited in their foresight, and in registering design parameters and constraints from upstream through to downstream processes. Generally, these methods do not consider assembly and construction constraints, nor do they account for the adaptation of projects into local conditions and the reality of real world analogue noise. Currently, there are few robust and efficient programming strategies for controlling multiple robots in customized semi-automated construction conditions. Challenges for such programming tasks include: a) a constantly changing environment (construction sites); b) much smaller production volumes (buildings are one off products); and c) a much larger range of required tasks (Bechthold 2010). Our conjecture is that the next steps in digital design and robotic fabrication are to develop methodologies that consider computers and our robotics as collaborative partners in the design process, as having agency and the capacity to register contextual conditions, environmental analyses, and construction constraints in order to provide architects with design alternatives that fulfill complexly coupled criteria, such as environmental performance, structural efficiencies, and fabrication constraints (Shea, Aish, and Gourtovaia 2005).

This research presents our prototyping of an integrated design methodology that allows for validated simulations of the robotic assembly sequence to be integrated into the early phases of the design process. As a first step, we focus on coupling environmental performance simulations and robotic construction simulations for informing and optimizing a generative design process based on our multi-agent systems (MAS) for design work. We validate our framework by applying it to building envelopes (i.e., facades) of a set of commercial buildings representative of varying geometric forms. Building envelopes are among the most complex architectural components, combining aesthetic,



2 Timeline of Robotic Construction Applications: a) Felix Candela (1958), Los Manantiales Restaurant form works. Xochimilco; b) U.S. Construction Robotics (Robotworx (2012), Semi-Automated Masonry System; c) Gramazio Kohler Research (2014), Building Strategies for On-site Robotic Construction; d) Self Organizing Systems Research Group (2014), Termes Project. Harvard University; e) T. Bock (1998), Automatic generation of the controlling-system for a wall construction robot, Institute for Machinery in Construction, Karlsruhe; f) Obayashi Corporation (2006), Automated Building Construction System (ABCS), Japan; g) Zhang Jing (2013), Contour Crafting, USC; h) Achim Menges (2014), Landesgartenschau Exhibition Hall, ICD/ITKE Stuttgart.

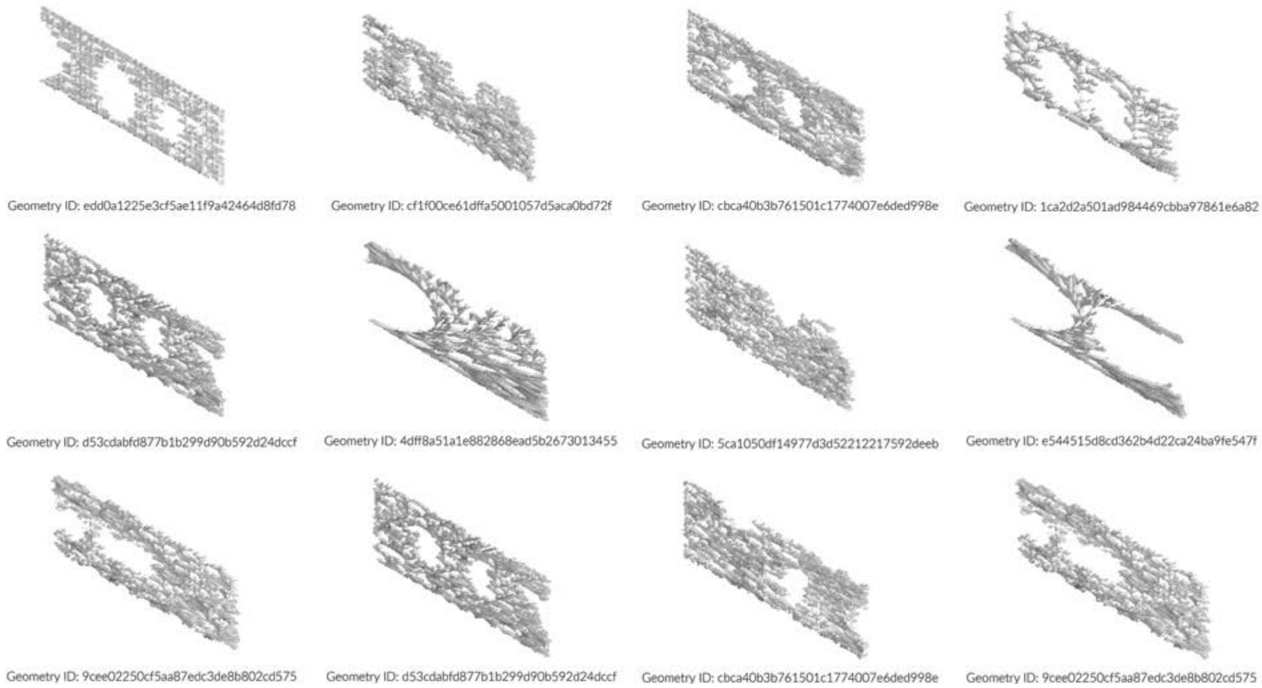
structural, environmental, and construction concerns, and are a use case where robotic fabrications will be readily adopted (Bechthold et al., 2011).

BACKGROUND

Towards robotic agency, from design to construction

Architecture has increasingly become the materialization of digital information instead of the materialization of drawings (Mitchell 2005). Computational design, especially associative parametric Computer Aided Design (CAD), introduced in the 1990s, allowed for design variation through the use of geometric constraints and manipulation of free-form geometries. Associative geometry and parametric design enabled the establishment of a schema of geometric dependencies for the building components, and thus controls for the behavior of such objects under transformations within a topological constraint (Gerber 2012; Oxman 2008). However, a building can be described through multiple levels of abstraction, of which geometry is just one among many, such as program typology, performance, construction technologies, or physical elements. Oxman points out that there is great potential for combining parametric modeling with performance-based design techniques in a top down fashion to exploit simulations for the modification of geometrical form towards the objective of optimizing candidate designs. On the other hand, there are integrative approaches that situate themselves between bottom-up and top-down processes, where based on nature and self-organization, agents are developed and fed with multiple types of input information (i.e., geometrical, structural, social), and are thus able to constantly adapt to required changes (Parascho et al. 2013).

Additionally, the utilization of large scale CAD/CAM manufacturing and robotics in the AEC industry is bridging the gap between what is digitally modeled and what could be physically realized. Such technologies allowed the production of non-standard components at almost the same price as standard (Kolarevic 2004). However, the AEC industry still remains a trade-oriented and labor-intensive industry with minimal automation of tasks. Research in construction-specific robots initiated in the 1980s in Japan, and focused on multiple construction-related activities. However, the unpredictability of the construction sites, hardware limitations, and high cost have resulted in few construction robots actually being used in construction sites (Maeda 2005). Related research has either focused on implementing different approaches for specific robotic construction subtasks, such as masonry placing robots (Bock et al. 1996; Steffani, Fliedner, and Gapp 1997), or for implementing large additive fabrication techniques, such as Contour Crafting (Khoshnevis 2004). These approaches use computer control to exploit the superior surface-forming capability of concrete and adobe structures, or to implement autonomous distributed robotic systems, which operate collectively in order to accomplish simple tasks



3 A subset of generated facade panel alternatives, with 2 and 3 openings on a planar input surface, which are high ranking in terms of environmental performance and therefore are tested for their constructability.

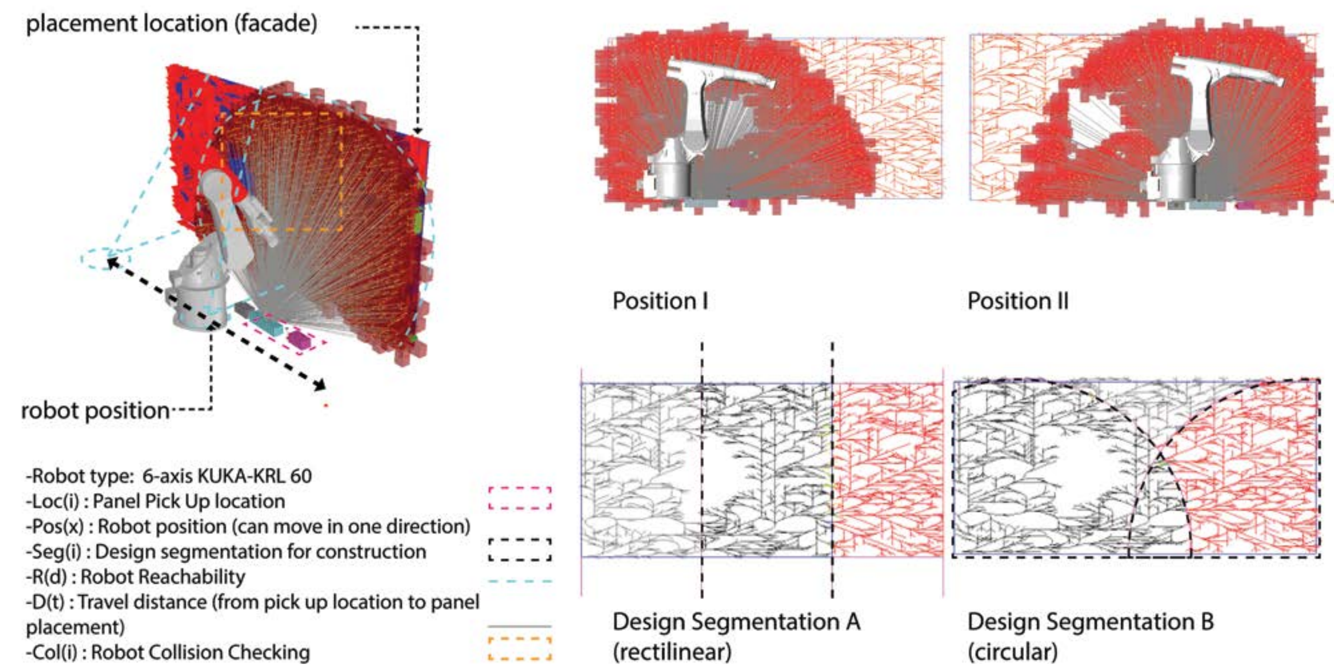
(Wawerla, Sukhatme, and Matarić 2002; Kube and Zhang 1993; Petersen 2014).

More recently in architecture, multi-functional industrial robots have become standard in automation precisely because, like personal computers, they have not been optimized for a single task but are suitable for a wide spectrum of applications (Gramazio and Kohler 2008). Perhaps most importantly, the widespread application of industrial robots has enabled the production of bespoke fabrications and mass customized manufacturing of architectural artifacts. This has been accompanied by a growing interest in reviving traditional techniques, or "digital craftsmanship," which leads to innovative yet regionally relevant architectural design that is formally intricate and complex, and often higher performing (Gramazio and Kohler 2008).

To date, digital design tools have mostly been utilized as a more efficient version of the drafting table, and not as an active aide in the design process (Oxman 2008). Current tools have incorporated performance feedback but only recently has research into integrating performance-based simulation for informing generative design become more accessible in practice (Malkawi et al. 2005). Although the tools for developing complex geometric forms are now commonplace, there is a lack of intuitive tools to enable designers to design and explore construction processes and particularly robotic solutions and their highly intricate and specific geometric configurations (Braumann and Cokcan 2012; Helm et al. 2014). This is because of first, the open-endedness of design problems and their ill-defined nature, which often requiring hard-to-compute synthesis; second, a general lack of a deep understanding and abstraction of fundamental shape-forming processes in nature that allow us to create tools to support our design intuition (Shea, Aish, and Gourtovaia 2005); and third, the rapid evolution of digital fabrication and robotic technologies on one hand, and the emerging necessity for architects to develop programming skill-sets on the other hand. Combined, these causes have hindered the growth and role of computation and robotics to influence design cognition and to further contextualize and incorporate them into architectural design decision making (Daas 2014).

RESEARCH METHODOLOGY & OBJECTIVES

The objective of this research is to develop a new digital design methodology as an extension of our multi-agent systems (MAS) for design method. The extension of our MAS for design supports the generation of optimized context-specific building components (i.e., façade panels) by integrating a bottom-up evolutionary MAS design strategy with environmental analysis and construction process constraints. The following research questions are asked: One, how can we better enable our generative design process by coupling it with automated robotic fabrication constraints more efficiently? Two, how can



4 Diagram illustrating the design of the experiment for the simulation of the robotic fabrication segmentation, positioning, and reachability, collision parameters of the construction agent.

we validate simulations that relate environmental and robotic constraints as performance drivers to improve the designer's decision-making process? Three, can we translate what we measure into a heuristic function for the design and incorporation of a robotic agency into the MAS for design approach of the research team.

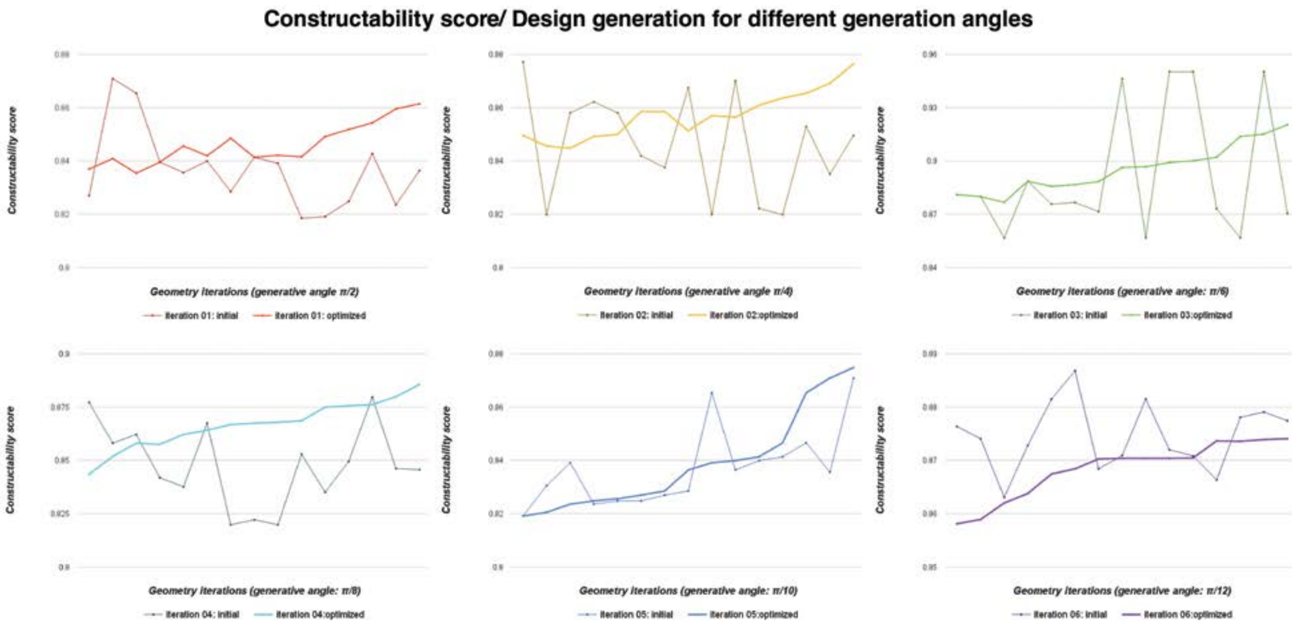
It has been shown that the development of a bottom-up design approach, where robot-operating strategies drive the geometric design and assembly process right from the beginning, can help designers by providing them with design solutions that are already optimized for constructability issues and can provide feedback on how a specific design might behave in the assembly process (Schwinn and Menges 2015). Therefore, we explore the hypothesis that robotic simulations can become an integral part of the digital design workflow, integrating robotic agency with other objectives, including environmental analysis and a heuristic measurement of construction efficiency. The research methodology is a progression from the development of a bespoke MAS for design, where the starting point has been to use a bottom-up strategy to generate design alternatives constrained by building type, building system, environmental performance targets, and user preferences (Gerber, Pantazis, and Marcolino 2015). Here, the system is further extended to include the geometric constraints (Figure 1) of the complex façade fenestration or louvering pattern, as well as the downstream robotic fabrication and installation processes.

MAS for Design and Robotic Fabrication Agency

The research is based on an existing prototype and custom programming, but extends the existing workflow—which is described in detail here (Gerber et al. 2015a)—by addressing robotic assembly. In order to bridge the gap between design generation and construction, and in anticipation of physical proofs of concept of our MAS for design system, we develop a bottom-up design strategy that incorporates robotic fabrication constraints, and considers how local geometric rules and design parameters of building components are coupled with: a) global constraints (i.e., facade surface, openings); b) environmental analysis, such as Daylight Factor Analysis (DLA) and Continuous Daylight Autonomy (CDA); and, c) robotic simulation feedback that conditions the assembly process.

Our work implements an MAS for design framework for the intrinsic modularity and level of abstraction necessary for the development of the agencies and for their capacity to operate within distributed environments (Gerber et al. 2015a; Sycara 1998). The system evaluates the generated designs by utilizing two types of environmental analysis: DLA as the basic metric to measure the amount of light entering a space, and CDA as an environmental performance measure that calculates the percentage of occupied hours per year, when the minimum luminance level can be maintained by daylight alone (Reinhart 2010).

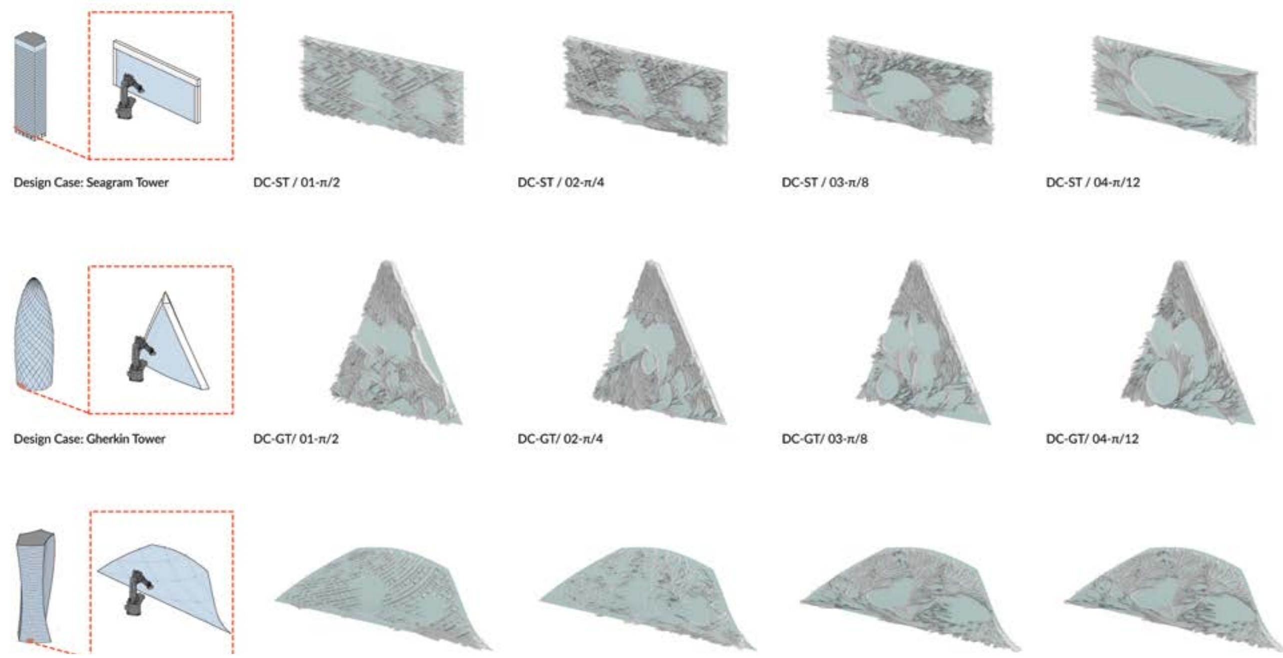
For the robotic simulation, we use a 6-axis robotic arm, the KUKA KR60H within the KUKA prc Grasshopper plug-in.



5 The graphs illustrate 6 different design generation cycles with variable angles with (bold, dark lines) and without (thin, light lines) the constructability score improvement over time per geometric iteration.

(Braumann 2011). MAS for design has four component agencies, which are modeled after specific design, analysis, and fabrication processes: a) a generative agent; b) a specialist environmental agent; c) a construction agent; and d), a coordinator agent (see Figure 1). The generative agent has a set of design parameters initially defined by the designer; for example, the design surface, orientation, panel length, generative angle, extrusion depth, and panel type preferences. This agent is tasked to iteratively create alternative geometries based on the input design parameters and context, which are updated on each run. The design parameters of the generative agent are defined by the designer, and are later conditioned by constraints imposed by the construction agent. The construction agent receives as inputs, the generative designs, which are evaluated to perform within a range defined in terms of the environmental analysis parameters described above. The system then performs the construction simulation and checks for constructability. Based on a constructability function and metric, the designs are ranked, and when necessary, the design parameters are updated and passed to the coordinator agent, forming one of the system's feedback loops. The objective of the construction agent is to find optimal positions for the robot that can facilitate and speed up the assembly process while decreasing collisions. This defines our ranking and heuristic function, further detailed below. The environmental agent performs two types of environmental analyses on the generated designs with the objective of combining the analyses and the passing of the analysis data—i.e., the lux values as CDA scores—to the coordinator agent along with a set of messages in the form of a report. The goal for the environmental agent is to increase the natural daylight entering a typical office space (the DLA), while keeping the lux values within a threshold (CDA) defined by the space typology and dimensions. The coordinator agent establishes the communication among the agents, and ensures each process is being called, completed, and data is passed in a controlled fashion.

In order to test our MAS for design and robotic assembly methodology, we divide our experimental protocol into two phases. In the first phase, the designer develops; a) an initial design component of a façade and defines a sub set of alternative panel types (three in total for this experiment); b) provides the following information as inputs for the generative MAS for design system: length, angle, probability for each panel type, and depth or extrusion of panel; c) runs N number of iterations using a hill-climbing optimization algorithm; and d), generates a solution space of design alternatives that are then evaluated for their performance across the DLA and CDA metrics. In the second phase the best performing designs are; e) passed to a robotic simulation software where different construction strategies are explored; f) collisions and errors are registered as negative scores in the ranking equation; g) designs are ranked based on their constructability in terms of construction time; and, finally, h) these scores are then passed back to the generative system for further optimization. In the next section, we provide an overview of how we performed our data collection and analyzed the simulation results, and how these help the designer reconsider



6 Image showing design alternatives for 3 different building case studies, which represent different levels of complexity (flat surface, curvilinear surface, free-form surface).

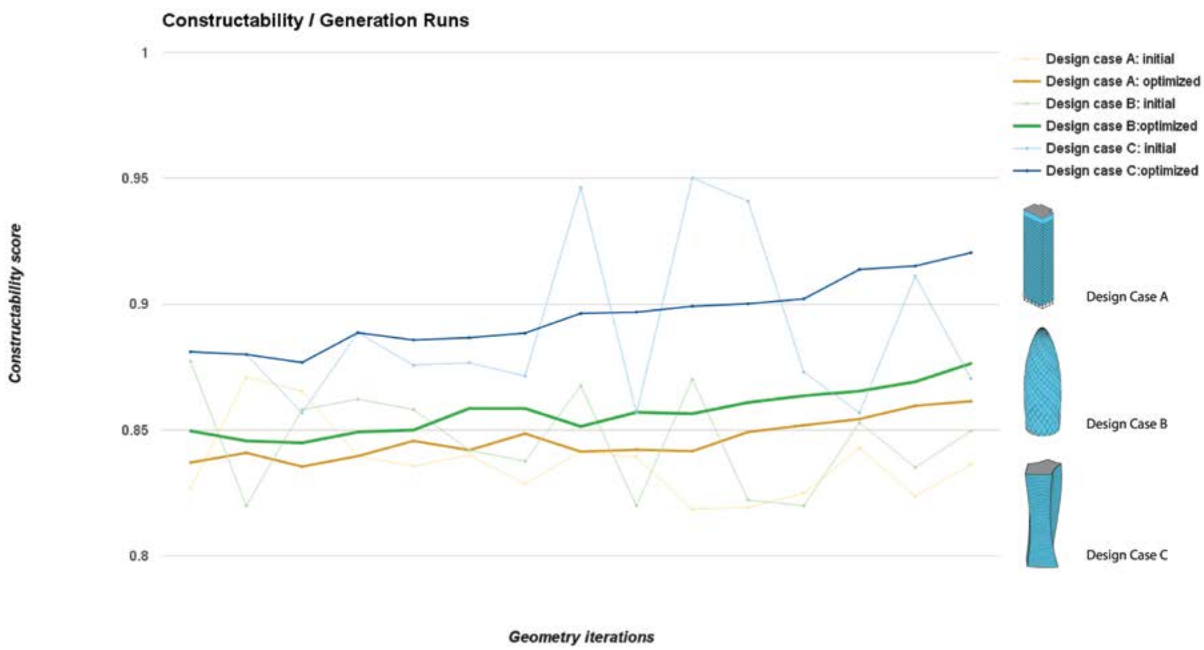
the integration of the whole design cycle of exploration, analysis, and simulated fabrication processes.

To demonstrate the feasibility of the extension of our MAS for design framework, a prototypical design tool, in conjunction with an environmental performance and robotic simulation workflow, is set up in order to generate a highly varied, environmentally optimized shading system for a typical office environment. The system uses Rhinoceros as a platform that allows the designer to communicate across different Integrated Development Environments (IDE) that the integrated MAS platform utilizes. Python and Grasshopper visual scripting editor are used to call the different agent processes which have been implemented in Java using Processing libraries (Reas and Fry 2007). For the creation and management of geometry created by the agencies, the system uses the IGeo library (see Figure 1 components a) and b)), an open source NURBS based library, in order to output geometries that can be further used for fabrication purposes (Sugihara 2014). The specialist agent is developed in Python and uses Ladybug and Honeybee environmental simulation tools (see Figure 1 components g) and h)) in order to combine three different environmental analyses: Energy Plus, Daysim, and OpenStudio (Roudsari, Pak, and Smith 2014). For the construction agent, the team implemented KUKA prc, a simulation plug-in for Grasshopper, to simulate the robotic construction sequence and complex fenestration assembly process. Finally, the coordination agent developed in Python establishes communication between the generative process (generative agent), the analytical process (specialist agent), and the simulation process (construction agent) by passing the analysis data and simulated results and messages back to the generative process, forming the culminating feedback loop in the system.

The work-flow is applied on the south facing façade of a typical academic office building, and is then further explored for other varied geometric forms. The following steps are followed in the design of our experiment:

1. The designer sets the input parameters and initializes a run of the generative system. The system implements a hill-climbing algorithm that searches for optimal window positions. At each iteration, the position of the windows is changed with a small increment in the surface domain of the facade. For each set of window positions, the system outputs one unique design, where the position of openings that provide more daylight to the interior are described as optimal. The data was collected by the system for 6 different generative angles: $\pi/2$, $\pi/4$, $\pi/6$, $\pi/8$, $\pi/10$, $\pi/12$. The generated designs are automatically passed to the specialist agent for lighting analysis. The system then performs two kinds of analysis, a) daylight factor analysis (DLA), and b) continuous daylight autonomy (CDA) for the generated designs.

2. Once the analysis is completed, the geometries with the highest ranking designs are sorted and passed to the robotic simulation.



7 Constructability metric in relation to design iterations for each of the different experimental case studies. Light curves represent the non-robotic-agent optimized constructability, bold curves represent the design generation inclusive of the robotic agency optimization.

3. The user selects the robot—in this case the 6-axis KUKA-KRL60—and defines the pick-up location and the robot axis of movement, here, parallel to the design surface.

4. A planning process is selected and the generated designs are segmented into groups based on the max reachability of the robotic arm. For the purpose of this research, only two different construction strategies are defined, thus dividing the generated design into rectangular and circular segmentations.

5. The robotic simulation is run and the system measures collisions, singularities, panels, and positions in order to develop the heuristic for the constructability agency. The following is the list of measurements and definitions in the heuristic function: a) Pos(x): the number of positions needed to assemble the whole façade and the number of max panels (Panels(n)) that the robot can place from a given robot position, where the best position is one in which the robot can place the maximum number of panels possible; b) Col(j): collisions between the robot and the already placed panels; c) Sing(k): singularity point positions that the robot can take while reaching a point in space that self-collide; d) D(t): and then calculates sum of travel distance from pick up location to panel placement (see Figure 2). Finally the constructability function is defined to be able to measure the performance of the construction process and rank the designs that depend on the parameters defined in steps a-d (see Equation below). Generally, more positions increase the construction time and thus result in lower scores. Singularities (k) harm the robot and thus are defined as impacting the negative score further. Based on a user-defined number of maximum collisions when placing panels, we eliminate (delete) panels or alter the probability for each panel that is passed as input to the generative agent for the next iteration.

$$con(runID)=(Panels(n)/Pos(x))/(D(t)*\sum Col(j)) - \sum (Sin(k))$$

The objective of the MAS for design prototype is to initially search the generated solution space for the environmentally efficient facade design alternatives, based on different window configurations and variable design parameters—in particular, the angulation of each fenestration piece. The most efficient results are passed into the construction simulation for testing and for feasibility evaluation. Through this feedback loop, at each iteration, the generative process is informed by both simulations and tradeoffs between the agents established through each agency's utility functions. In this way, the system iteratively limits the solution space of possible better performing designs by constraining the design parameters to those that yield combined constructible and environmentally efficient outcomes.

EXPERIMENTAL RUNS

The team has completed a pilot study of the system and gathered initial results based on running the generative and analytical loops of the system for 450 cycles for three different case studies that vary in terms of geometry (Figure 6). The duration of each generation analysis cycle is approximately 5 min, including the geometry generation and the environmental analysis, while the robotic simulation cycle is approximately 10 min. Six different generative angles were tested to explore the capacity of our system to create an expanded and highly varied solution space of 450 unique geometries. The 10 highest-ranking designs from each cycle were selected and passed to the robotic construction agent. One pick-up location for all three types of panels was set and the range of possible segmentation positions was set from two to four. By segmentation position, we refer to the way we break up a generated design into parts, based on the work volume of a specified robot. In this study, we only looked into circular design segmentation based on the max reach of the available industrial arm.

Based on the simulation and the constructability heuristic function, the generated designs were improved for construction purposes either by eliminating panels or by changing the sequence of panel types. The updated parameters for each design were stored in XML files and were passed back to the generative agent. In Figure 5, graphs of the constructability score of the initial and improved geometries are presented for all the six different generation angles, while in Figure 7 we present the results for the three different case studies. It is observed that the constructability score is highly variable with the initial conditions, but becomes a line with zero or positive slope for the improved geometries across all the generation configurations. From the results on a flat façade surface, we can observe that geometries with generation angle $\pi/10$ performed better overall in terms of their constructability scores over time, as the deviation from initial to final score is the largest compared to the rest of the runs by a delta of 6%. In the initial runs, the constructability score from one design iteration to the next ranges from 0.1 to 0.6 in some cases, while in the optimized cases it drops below 0.15 and is constantly improving.

From the obtained results on different input geometries (flat surface: case A, curvilinear: case B, free form surface: case C), we can observe that for the planar geometry (design case A), the constructability score is higher, which means the system could find easier ways to assemble the façade panels, as expected, though the free form case seems to behave better than the curvilinear example (Figure 7), requiring further investigation. Thus in this work, we show that the system at this stage, with the integrated heuristic for constructability, is able to generate façade panels for different input geometries and output results that are performing well environmentally but are also optimized given a set of robotic fabrication constraints. Therefore, the designer can obtain feedback for multiple design objectives, based on both the environmental and construction simulation performance. As a result, designers can make more informed design decisions of one alternative over another, but also establish more seamless and efficient communication with façade engineers and fabricators. The system continues to be tested, validated, and further integrated.

In these experiments, a number of limitations are worth pointing out. Firstly, for reasons of simplicity, only one type of design segmentation was simulated and tested on the zero curvature (façade) surface domain and then the ruled curving and non-uniform domains. Moreover, at present the system is not fully automated and it still requires the designer to work across multiple interfaces. On occasion, during the generation of a design alternative, the criteria for creating a complete fenestration pattern across the domain of surface, while faced with a local minima problem within the hill-climbing algorithm, requires the manual deletion of collision points to enable the continuation of the pattern and design. Last but not least, in order to validate the results, we are planning to perform a physical experiment in order to be able to cross-reference the simulated with the physically obtained analogue and tectonic results.

DISCUSSION AND NEXT STEPS

At this stage of the research, we have successfully developed and tested an integrated MAS for design system. So far, the pilot study provided us with an intuition of how one design parameter, the angulation of the panels, can affect the design generation and the behavior of the system. We will continue to gather and analyze the data in order to further refine the heuristic function, as well as the definition of the agencies and their negotiation. As a next step, the full automation of the geometry and data passing across all agents will be further implemented. Another crucial enhancement to the MAS for design system is the further refinement of the generative agent to always output valid solutions given the feedback from the construction and simulation agent.

More work will also continue to revise and validate the results of our constructability utility function and to further test segmentation strategies. We will need to examine each parameter separately—doing so by running iterative simulations for each of the design parameters—and will check the behavior of the system, first in isolation, then in careful combination. Finally, the team will run simulations on a conventional existing façade design and compare our methodology in order to be able to benchmark the contribution of the work from design exploration, through multi-objective optimization, to efficient fabrication.

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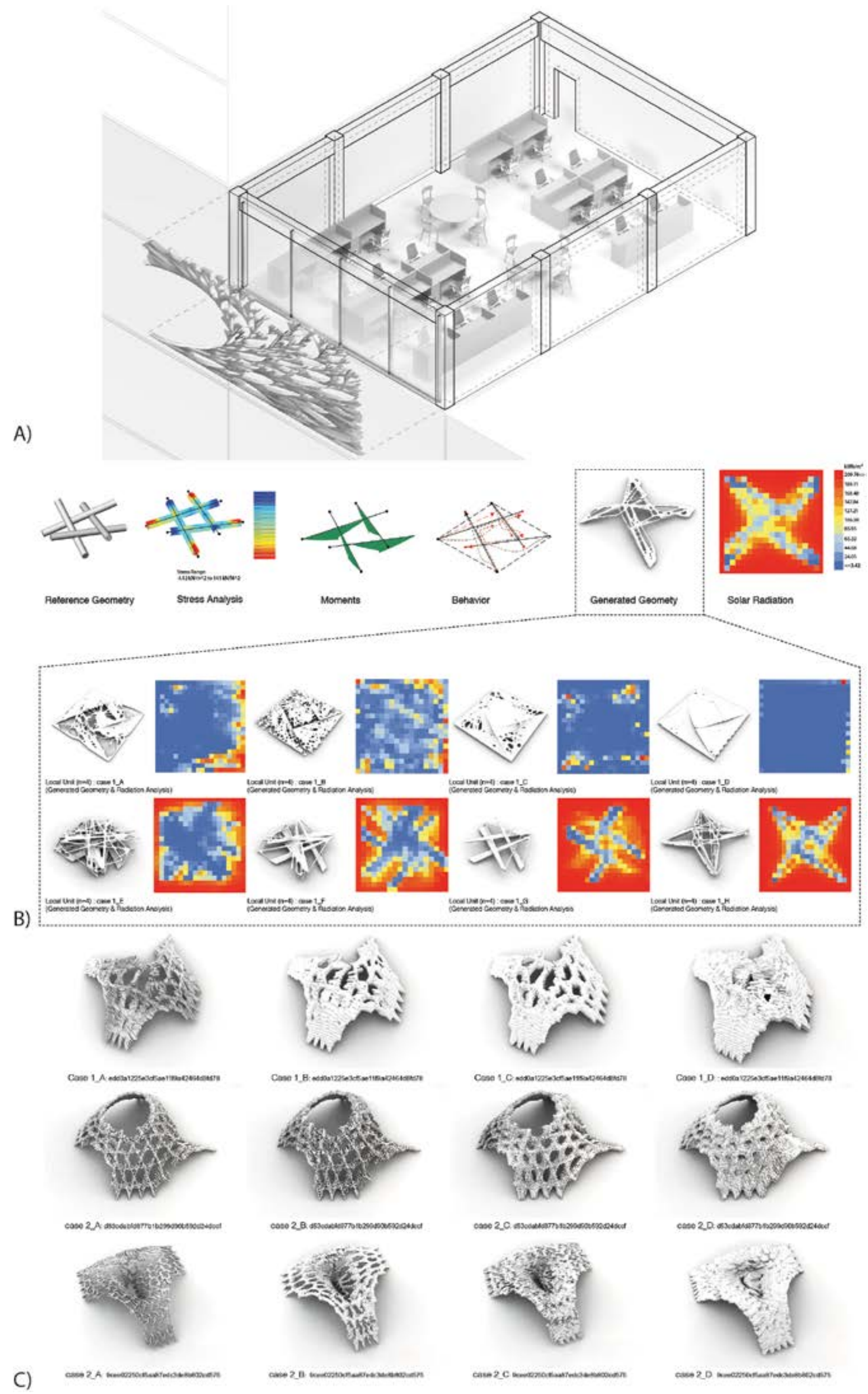

8 These images illustrate the Multi-Agent Systems for Design research thrusts and domains. This work presents research on the prototyping of multi-agent systems for architectural design of building envelopes, reciprocal frames, and form found shells. It presents a design exploration methodology at the intersection of architecture, engineering, and computer science, and focuses on bottom up generative methods coupled with multi-objective optimizing performance criteria; including for a) geometric complexity, b) objective functions for environmental and structural parameters, and c) robotic and digital fabrication. The Multi Agent System for design research has been developed, which looks at; A) building envelopes as a domain of interest for highlighting pro environmental capacities; B) local structural shell units in the form of reciprocal frames and in particular reciprocal frames as elements that can be used as form work for digitally deposited matrials that perform structurally as well as environmentally through voxelized porosity; and C) the combination of form found shells and the recirpocal frames to design explore and optimize the multi-objective aspects of these design space compelxities, specifically for structural matetrial minimzation in a trade off for lighing and temperature effects beneath the canopy. The work on enveloes and shells progress from non structural systems to structural systems and to the robotic implementation presented in this paper.

and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. We would like to thank Professor Burcin Becerik-Gerber for her contributions in advising on the topic, and Alan Wang, an undergraduate researcher at USC, for his support in the development of the system and process.

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IMAGE CREDITS

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Figure 2: Timeline of Manual&Robotic Construction Applications. All images retrieved in July of 2016 from:
a) https://gr.pinterest.com/pin/294141419383708208/;
b) http://www.bdcnetwork.com/robots-drones-and-printed-buildings-promise-automated-constructionc);
c) http://gramaziokohler.arch.ethz.ch/web/e/forschung/273.html;
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g) J. Zhang, B Khoshnevis, "Optimal machine operation planning for construction by Contour Crafting", Automation in Construction 29 (2013) 50–67; h) http://icd.uni-stuttgart.de/?p=11173

Dr. David Jason Gerber is an assistant professor at USC's School of Architecture with a courtesy joint appointment in the Sonny Astani Department of Civil and Environmental Engineering. He conducts NSF and corporate funded research at the intersection of design, science, and computing for Architecture. From 2008 to 2010 Dr. Gerber was a Vice President at Gehry Technologies Inc., a leading innovator in Building Information Modeling and building industry technology consulting. Dr. Gerber has worked as an architectural and urban designer in the US, Europe and Asia, for the Steinberg Group, Moshe Safdie, and as a project architect for Zaha Hadid Architects. He has been awarded research fellowships at MIT's Media Lab, as well as numerous teaching and research fellowships at Harvard University Graduate School of Design and as Harvard University's Frederick Sheldon Fellow. Dr. Gerber studied archtiecture at the University of California Berkeley (BA 1996), the Architectural Association in London (MArch 2000) and completed his design compotuing research and doctoral studies at Harvard University (MDesS 2003, DDes 2007).

Evangelos Pantazis is currently pursuing a PhD at the Viterbi School of Engineering at the University of Southern California. His research lies on the intersection of architecture and engineering and computational modelling and focuses on the use of Multi Agent Systems for building design . Evangelos holds a Masters of Advanced studies in the field of Computer Aided Architectural Design from the ETH in Zurich (2012). He received his Diploma in Architecture with honors from Aristotle's University of Thessaloniki (2010), and has also graduated from the MOKUME jewelry design school in 2007, where he was trained as a jeweler.