Design Agency

Prototyping Multi-Agent Systems in Architecture

David Jason Gerber, Evangelos Pantazis and Leandro Soriano Marcolino

University of Southern California
{dgerber, epanatazi, sorianom}@usc.edu

Abstract. This paper presents research on the prototyping of multi-agent systems for architectural design. It proposes a design exploration methodology at the intersection of architecture, engineering, and computer science. The motivation of the work includes exploring bottom up generative methods coupled with optimizing performance criteria including for geometric complexity and objective functions for environmental, structural and fabrication parameters. The paper presents the development of a research framework and initial experiments to provide design solutions, which simultaneously satisfy complexly coupled and often contradicting objectives. The prototypical experiments and initial algorithms are described through a set of different design cases and agents within this framework; for the generation of façade panels for light control; for emergent design of shell structures; for actual construction of reciprocal frames; and for robotic fabrication. Initial results include multi-agent derived efficiencies for environmental and fabrication criteria and discussion of future steps for inclusion of human and structural factors.

Keywords: *Generative Design, Parametric Design, Multi-Agent Systems, Digital Fabrication, Form Finding, Reciprocal Frames*

1. Introduction

An important paradigm shift is occurring in the architecture, engineering and construction (AEC) industry, one of less reliance on the mass produced to that of the 'infinitely' computed and customized [32]. The shift is characterized through the change in dependency on fordist modes of production to that of the post-fordist manufacturing technologies and possibilities [15]. As serial production of similar building elements become less necessary for design, given mass customizable digital fabrication processes, the types of design inquiry, exploration and production become ever more inclusive of complexity. As data and analysis become more readily accessible to design process, a parallel and companion shift is also occurring; one of a growing interest by designers to utilize performance, fabrication and user related feedback as new types of 'design agencies'. Further effects of the shift computing and fabrication advances have brought to architecture, is that of our ability to model, simulate, and incorporate techniques and theories from biology and computer science, here the incorporation of multi-agent systems (MAS). In order to be able to design and build highly articulated and equally resource efficient structures our work seeks to harness the 'design agency' paradigm shift's key features.

The first feature can be characterized by burgeoning access to 'infinite' computing for generation, search, ranking and analysis of expansive solution spaces of designs. The second feature can be characterized by the ability to conceive design solutions with vastly more intricate and perhaps higher performing geometry which are no longer constrained by off the shelf elements and the fordist paradigm. Arguably these paradigmatic trends are in large part due to the rapid evolution of computational design tools such as associative parametric modeling [16], algorithmic and generative design methods [42], and finally rapid additive and robotic manufacturing. Together these features have provided architecture and the entire AEC with expanded design solution spaces and richer interdisciplinary collaboration and integration. In concert with increased integration and accuracy of design models, the increasing availability of computer aided manufacturing and digital fabrication in architecture continues to enhance the possibilities and economics for the production of highly articulated, performatively tuned building elements, systems, and assemblies. Computer Aided Design and Engineering (CAD/CAE) enable architects and engineers to integrate early in the design phase by improving upon model fidelity, ease of collaboration and furthermore provide solution space search and optimization approaches through the integration of simulation and computer science techniques [24]. In addition, the recent introduction of industrial robots into architectural design discourse and processes is marking a transition from job-specific to flexible, programmable and extensible robotic-fabrication processes resulting in additional novel forms of agency, both for geometric intricacy and for the informing of these forms performatively. With these contemporary design technologies – parametric modeling, multidisciplinary design optimization (MDO), agent based simulation, and robotic and rapid additive manufacturing – architecture is realizing the potential to harness and manage complexity through distributed design models rather than reducing via an over reliance on simplistic and deterministic models. The design complexity our research addresses includes the coupling of human, spatial, environmental, structural, material and emergent behaviors. This is achieved in large part within simulations used in design practice for evaluating different performance factors such as cost, environmental and structural efficiency, as well as social utility [44].

Our research presents an evolution of the work from parametric design and MDO through to Multi-Agent Systems (MAS) for use in architectural design. The research investigates the affordances and convergences between architectural form generation – parametric and generative, digital fabrication, and multi-objective optimization and search. It does so with an interest in complex geometry and complexly coupled objective functions for generating intricate and articulated performance for architecture. The primary objective of the work is to introduce and test a hypothesis that a MAS framework can lead to informed and improved design process and architectural outcomes without a reduction in terms of inputs used and their geometric outcomes. The inputs include user, environmental, structural, and fabrications parameters, constraints and objectives. Our vision is of an integrated approach for architectural design where multi-agent algorithms are combined with parametric models to coordinate and negotiate for improved design decion making. The paper presents a developing framework and series of experimental studies to benchmark and test the vision. We started by exploring and optimizing the design of building envelopes by aggregating the opinions of multiple agents through voting [27], and in this paper we further elaborate on the agent algorithms and fabrication of window panels and funicular shell structures. The sequence of experiments illustrate research tasks including framework definition, form finding, algorithm design, simulation, the future use of immersive virtual environments (IVE) for data capture and digital fabrication for one to one construction. Their combination serve as a proof of concept of the framework in its current form and lay the foundation for further research steps, which include performance evaluation, multi-objective optimization, and further refinement and development of multi-agent algorithms for design.

1.1 Design Research Contexts

Our work is focused on the architectural cases of shell structures and façade panels. These are chosen in order to measure impact upon indoor environmental and social conditions as well as for criteria of structural performance and fabrication due to the geometric complexity and structural logics shell structures engender.

Historically, empirical methods allowed for the calculation of funicular shells, while building techniques emerged and developed alongside in order to master the geometric complexity of such forms [12]. In the 20th century, digital technologies and new materials rendered such traditional techniques virtually obsolete. However, designers and engineers such as Felix Candela, Pier Luigi Nervi, Antoni Gaudi, Frei Otto, and Heinz Isler, Erwin Hauer provide precedent and inspiration for the framework. Through innovating physical and empirical testing and form finding methods these pioneers proved ability to build a wide variety of efficient and yet geometrically complex and multi-purpose shell structures and panel systems [1, 26]. The contemporary advancements in computation and the capability to model and analyze complex non-Euclidean geometries has brought about the resurgence of interest in their methods and the related traditional techniques.

In our research, we explore not only computational design approaches for generating such structures and systems, but we also study actual fabrication through 3D printing and automated robotic construction. The other test case is that of non-structural building components and in particular geometries for tiling the envelope components for the purpose of enhancing environmental conditioning (i.e., generating window panels). Our interest in the second design context is in part predicated on the ability to measure human subjects and their behavior to indoor environmental factors through immersive virtual environments (IVEs), for gathering real world data to be used in our multi-agent system simulations.

The motivation of this research is in part a reaction to the disconnect between digital techniques and algorithms for designing with complexity that produces geometric performance, and that of analogue fabrication and materiality [21]. While there is research to integrate structural and environmental performance feedback through simulations [38] our work looks to advance this discourse through the development of multi-agent algorithms. Furthermore, new possibilities for rediscovering the potential of designing efficient shell structures by revisiting traditional structural techniques is becoming possible [37]. Along with the challenges of developing methods to work with complexity for articulating geometry our work also seeks optimizations in these structures and systems that minimize their environmental impact while incorporating the dynamics of human behavior and preferences. Finally the work looks to full scale prototyping as a means to provide further tangible value to architecture through demonstrating the links to fabrication and tectonics.

2 Literature Review

To provide background to the research an overview of contemporary computational tools and techniques for form finding, for performance evaluation, shell structures, as well as precedents and literature influential to our MAS framework is presented. Work related to the development of our framework including precedents from immersive virtual reality (IVE) and digital prototyping and robotic fabrication workflows are also highlighted and gaps are introduced.

2.1 Form Finding Tools and Techniques

The structurally efficient free-form design challenge lies in determining the 'right' structural shape that will resist loads within its surface without the need for extra structural systems. Of all traditional structural design parameters such as material choice, section profiles, node type, global geometry and support conditions, the global geometry predominantly dictates whether a curved surface will be stable, safe and stiff. Precedent work in the field includes the works of Gaudi, Nervi, Candela, Xenakis. Otto and contemporary work from Ochsendorf, Block, and Sasaki, to name but a few [1, 10, 33]. As just one example from these precedents Heinz Isler made extensive use and analysis of physical scale models, which were cast in plaster upside down, and then scaled to full size. Isler believed that physical models built physically ensure a more holistic simulation of the problem although they posed the ensuing challenges of accuracy and scalability of material and mass.

In part inspired by Gaudi's physical hanging chain models, work at MIT introduced the use of particle spring systems for simulating the behavior of hanging chain models digitally for finding structural forms composed of only axial forcers [11, 16]. Another critical precedent is the work of Daniel Piker who introduced an intuitive visual scripting tool, Kangaroo that enables digital form finding. Kangaroo, a non-linear "physics based" engine, is embedded directly within the Rhinoceros-Grasshopper computer-aided design (CAD) environment, enabling geometric forms to be shaped by material properties, applied forces and interacted with in real time. By embedding rapid iteration and simulation in the early-stage design process, Kangaroo allows for a faster feedback loop between modification of design and engineering analyses [31]. This is particularly useful for the design of structures involving large deformations of material from their rest state, such as tensile membranes, bent-timber grid shells and inflatable structures. Kangaroo can also be applied to the interactive optimization of geometric and aesthetic qualities that may not themselves be intrinsically physical.

Another research group lead by Philippe Block has developed a structural form finding software package -Rhinovault- that implements the Thrust Network Approach (TNA) to create and explore compression-only structures. It uses projective geometry, duality theory and linear optimization, and provides a graphical and intuitive method, for adopting the advantages of graphic statics, for three-dimensional problems [5]. Rhinovault, is based on relationships between form and forces expressed through diagrams that are linked through simple geometric constraints: a form diagram, representing the geometry of the structure, reaction forces and applied loads, and a force diagram, representing both global and local equilibrium of forces acting on and in the structure [43]. Rhinovault takes advantage of the relations between force equilibrium and three-dimensional forms and explicitly represents them by geometrically linking form and force diagram.

From these precedents we observe an evolution from physical simulation methods and historical form finding techniques to a series of contemporary form finding tools that implement contemporary mathematical models and digital simulations for computing and analyzing form. We note that in the case of TNA, linear optimization is used whereas in the case of Kangaroo the geometry optimization is non-linear. Moreover TNA's reduction of the problem into two dimensions offers a more efficient computational model for computing the force distribution.

2.2 Historical Building Techniques

Key characteristics of two precedent traditional building techniques, that of stereotomy and that of reciprocal frames, are described in brief in terms of how they can inform the agent behaviors as well as for their potential use in a robotic manufacturing context. Both techniques are of particular interest given the challenge they bring to the motivation for enhancing geometric and performative intricacy and complexity. Our research is in part motivated by these techniques which we conjecture within a MAS framework offer new possibilities for the conceptualization, materialization, and optimizations of shell structures and highly articulated building envelopes.

2.2.1 Reciprocal frames

The reciprocal frame is a three-dimensional structure consisting of mutually supporting sloping beams placed in a closed circuit [23]. It is a structural system, formed by a number of short bars that are connected using friction only. Most importantly, the reciprocal frame can span many times the length of the individual bars [30]. The application of the reciprocity principle requires: a) the presence of at least two elements allowing the generation of forced interactions; b) that each element of the assembly supports and is supported by another one; and c) that every supported element meets its support along the span and never at the vertices in order to avoid the generation of a space grid with pin joints. Structures that conform with the above requirements are called *'reciprocal'* [34].

2.2.2 Stereotomy

Stereotomy is the technique of processing solids such as stone, to build vaulted architectural systems. The word stereotomy or 'cutting solids' appears in 1644 and per Jacques Curabelle represented the cultured abstraction of something handed down through the centuries as "the art of the geometrical line" [14]. By carefully examining the principles of the stereotomic discipline, stereotomy is regulated by three distinctive and invariant principles: a) *Pre-figurative invariant*: the subdivision capacity in appropriate sections of a vaulted system; b) *Technical/geometric invariant*: the capacity of geometric definition of an architectural system and the related structural components (ashlars) through its realization constraints (projective technique and cutting technique); and c) *Static invariant*: the capacity of providing static balance of the architectural system through dry-stone jointing (graphic and mechanic static of rigid structures). According to these three principles, capable of being variously ordered, one can discriminate between general stone architectures and stereotomic ones [14].

Stereotomy and reciprocal frames represent two building techniques, which take advantage of local resources and material capacities. Their technical complexity led to near extinction in architecture after the introduction of fordist standardization and the dominance of concrete and steel. Recent research has shown that the application of robotic manufacturing and digital fabrication can be appropriated to offer an opportunity to reconsider them in a computational context [22]. Recent developments in digital fabrication processes allow for the generation and materialization of complex information driven geometries as is seen in the work of M. Burry, G. Epps, W. McGee and A. Menges to list a few [8, 20, 29, 41].

2.3 Multi-Agent Systems for Integrated Design

Multi Agent Systems (MAS) and agent based modeling (ABM) techniques are becoming an avenue for exploring non-linear, emergent, and behavioral modeling in architecture. Exemplary real world problems where agent based approaches have been implemented involve open systems whose main characteristics are that the structure, often described through their network topology, is capable of dynamically changing and their components are not know in advance. De Loach, who introduced the Multi agent Systems Engineering (MaSE) methodology, uses a number of graphically based models to describe system goals, agent types and behaviors and argues that most of the current research related to intelligent agents has focused on the capabilities and structure of individual agents which is not sufficient enough for solving more complex, more realistic and large scale problems. He argues, in order to solve such problems, these agents must work cooperatively with other agents and in a heterogeneous environment [11]. Sycara suggests that if we assume a problem domain, that is particularly complex, large or unpredictable, such as architecture, then it can be reasonably addressed by developing a number of functionally specific and modular components (agents) that are programmed to solve a particular task [40].

Recent research in the field of Artificial Intelligence has tested a theoretical model, which suggests that voting across agents can provide a higher number of optimal solutions for complex design problems. This model has been applied in an architectural context with the aim to provide designers with higher ranking design alternatives in the early design stages [27]. Despite the extensive precedents on MAS in the fields of software engineering and computer science in general, the introduction of ABM and MAS in architectural design is albeit relatively recent and has mostly focused on generating complex self-organizing geometry through the implementation of a limited set of algorithms. The body of precedents include both researchers/research units and practitioner's whose work is predominantly based on Craig Reynolds' flocking algorithm [3, 15, 36, 39]. These precedents have mostly focused on the generative aspects of the simulations and not on the impacts of performance criteria nor the incorporation of human and real world data, gaps we highlight and anticipate addressing through our MAS framework.

These architectural precedents generally achieve the geometric complexity and aesthetic but remain arguably still in their infancy when compared to the advances we see in computer science. The applicability of ABMs in different stages of the architectural process have yet to be fully identified which highlights a noticeable gap, again that the majority of the precedent work has been limited by investigating only behavioral models based on variations of Reynold's algorithm. By contrast there is considerable work from engineering and construction researchers where ABMs and MASs have been applied to addresses logistics and negotiation driven optimizations [2]. Our work in part identifies a critical opportunity for architecture to utilize MAS affordances where behavioral design methodologies are not simplistically a negotiation of geometries but of geometry coupled with local and global performance objectives. The research perceives this as a significant shift from the direct and top-down invention of form or organization to intensive, intrinsic, bottom up, and collectively intelligent processes of formation, generation and rationalization that we conjecture can lead to higher performing solutions without a reduction of geometric intricacy and articulation [29].

2.4 Fabrication Aware Form Finding

Currently there are more than a million multi-functional robots in use and the number is rising. An obvious observation can be surmised, namely that the programmable and extensible character of robotics offers architects the opportunity to create evermore complex and yet economically viable projects. There are a number of significant precedent research teams who have influenced our methodology and design of the MAS framework [4, 29].

For example, Gramazio & Kohler investigate digital materiality and how robotic manufacturing can lead designers to shift from designing standardized forms to designing material processes intrinsically for the non-standard and therefore potentially higher performing [17]. Based on the assumption that architecture is mostly accumulation of material they implement industrial robots in order to precisely accumulate material where needed and thus weave form and function directly into building components. Their research includes a range of experiments at one to one scale with different materials and custom fabrication workflows.

Another example is Achim Menges who investigates how concepts from morphology and biology can be transferred into architecture with respect to design computation and robotic fabrication [29]. Matias del Campo explores autonomous tectonic systems without the need of indexical formwork. By setting up rule sets that trigger a specific response of a robotic system he investigates deposition of thermoplastic material behaviors that lead to the erection of spatial configurations more efficiently [15].

Our review also highlights a growing number of integrations of robotic manufacturing and design exploration methods being developed in architecture. This includes the development of interfaces and of research projects [6, 13]. Critical to our framework is the inclusion of the fabrication constraints and the sequence of the fabrication activities as a feedback loop to the MAS design as discussed in the following methodology and experimental design sections.

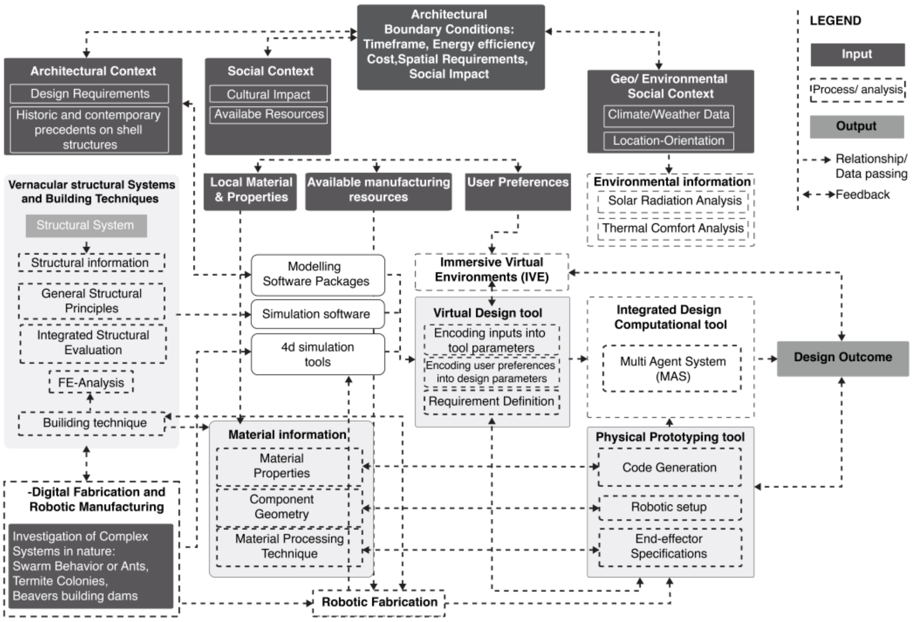

Fig. 1. Research Framework Diagram illustrating our integrated MAS approach. The diagram illustrates the inputs, processes, design context constraints and outputs.

3 Research Methodology

Our research methodology is based on a series of survey, theoretical, design experiment and analytical activities. It is also a continuation of existing research on the multi-objective nature of complexly coupled parameter problems. The research methodology is an evolution from parametric design, to MDO, and now towards the incorporation of MAS. At this point we are introducing and developing a framework and a set of experimental designs that operate as initial proof of concept. In this section we introduce our main hypothesis and our proposed MAS framework (see Figure1), while in Section 4 we present our initial algorithms for the agents within this frame work. Generated design outcomes and detailed results are presented in Section 5.

3.1 Multi-agent Framework

The research hypothesizes that geometric and multi-objective complexity can in fact lead to novel high performance design solutions through MAS enabled design generation, optimization, ranking and search. To further decompose our hypothesis, the challenge for contemporary architects is an issue of managing complexity and of equal importance, the inclusion of real world complexity rather than the prevalent use of reduced models. Instead of perpetuating reliance on reduced models and exaggerated margins of error in design, our goals is to prove that well formulated parameter design problems can be supported by MAS with follow on performative results.

Due to the complexity of the design problems, we argue that single agent solutions may not be enough, as the development of such a design agent that can handle all aspects of design seems to be inherently hard. Hence, we envision a system with multiple agents, each one responsible for a different aspect/objective of design. These agents could be completely decoupled, if the design "tasks" (i.e., aspects) are completely independent. However, the complexity of design seems to indicate that negotiation mechanisms are also necessary. While in this paper we present initial algorithms and results for some of these design agents (see Sections 4 and 5), the development of the negotiation mechanisms is still a work in progress.

In a parallel research, however, we explore the potential of plurality voting (i.e., pick the option decided by the highest number of agents) when aggregating the opinions of multiple design agents[27-28]. However, in [7] all agents are using heuristics for the same optimization problem, so it is still not clear if plurality would be the best option when agents are responsible for different design aspects. Other alternatives to voting would include argumentation (i.e., agents use a logic-based language to defend and/or refute arguments) [45]; or hierarchy-based rules, where an agent would be allowed to change the design of others that are bellow in the hierarchy (for example, the agent responsible for designing forms that can actually be constructed should have a higher priority).

Our proposed framework, however, goes beyond teams of agents that negotiate into solving complex design problems. We argue that dynamic data sets are also crucial. Designs exist in a physical world with complex interactions between the design model and the "real" world, and of course are used by actual people. Therefore, two types of information seem to be essential: (i) Environmental Analysis; (ii) User preferences. Each change in a design will also affect these data, besides their natural change (the light that illuminates a surface changes according to the season, a certain person may change her preference over time or according to a certain task that she must perform, etc.). Hence, we envision systems that not only use environmental analysis and user preferences data as input, but also that continually read such information and adapt according to the current information, in a continuous feedback loop.

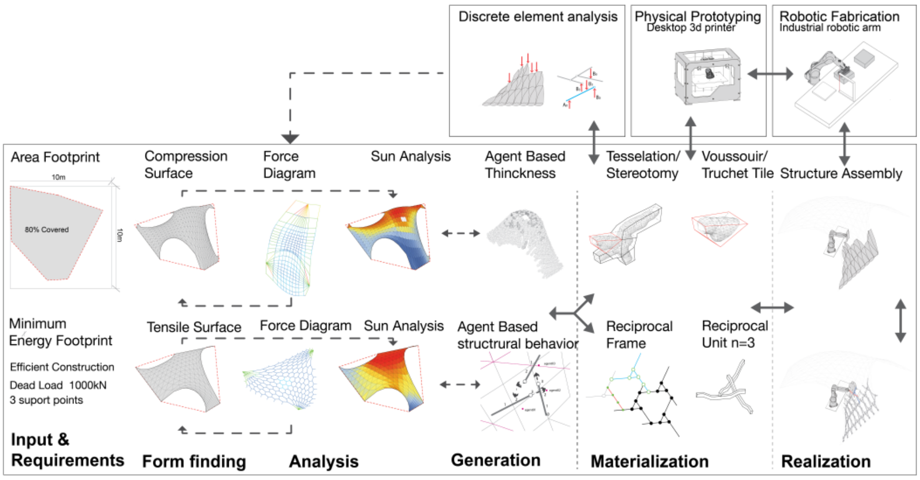

Fig. 2. Illustration of the MAS framework and detailed workflow for the shell and reciprocal frame design context. It includes the design context, form finding, analysis, constraints and rules, agent based results, physical prototyping through to robotic fabrication.

Finally, we also envision the construction of the designs proposed by the MAS system. Hence, such agents would also have to verify the constructability of the proposed designs. Note, however, that this can be easily incorporated in our framework by having a construction agent, and forcing the other agents to continuously negotiate with such agent in order to ensure constructability. We go beyond manual construction and consider automatic construction of the designs by robotic systems (as we will discuss in Section 3.2). In Figure 1 we can see a high-level view of our proposed framework.

We are currently investigating the framework in the design of shells, façade panels and reciprocal frames (while in [27] we explore building envelope components), all the way from design in simulation through to actual construction. In Figure 2 we can see one instantiation of our framework, focusing on designing and constructing shell structures. We test our hypothesis by applying our framework to experimental cases that measure the impacts of MAS for the structural, environmental and fabrication parameters. In Section 4 we introduce our initial algorithms for three design agents within our framework: one responsible for creating a window panel that regulates the amount of light that enters an environment, one responsible for emerging a geometric structure according to an environmental analysis, and one responsible for a generation and materialization of a perforated reciprocal frame structure.

3.2 Immersive Virtual Environments

Finally, we also anticipate using data from preferences of users. In order to obtain such information, our MAS framework includes the use of Immersive Virtual Environments (IVE) and technologies to effectively allow end-users to respond to design alternatives, and therefore provide another real world data stream and feedback loop through their evaluation. Researchers have proposed the need for the AEC industry to adopt the concept of User Centered Design (UCD) by involving users early on during the design phase [7] and have emphasized the need for accurate measurement of occupant behavior [19, 35]. By creating a better sense of realism through an IVE's one-to-one scale, architects and engineers can incorporate IVEs in their work processes as a tool to measure end-user behavior, understand the impact of design features on behavior, as well as receive constructive user feedback during the design phase. Previous research has suggested that these environments have the potential to provide a sense of presence found in physical mockups and make evaluation of numerous potential design alternatives in a timely and cost-efficient manner [18].

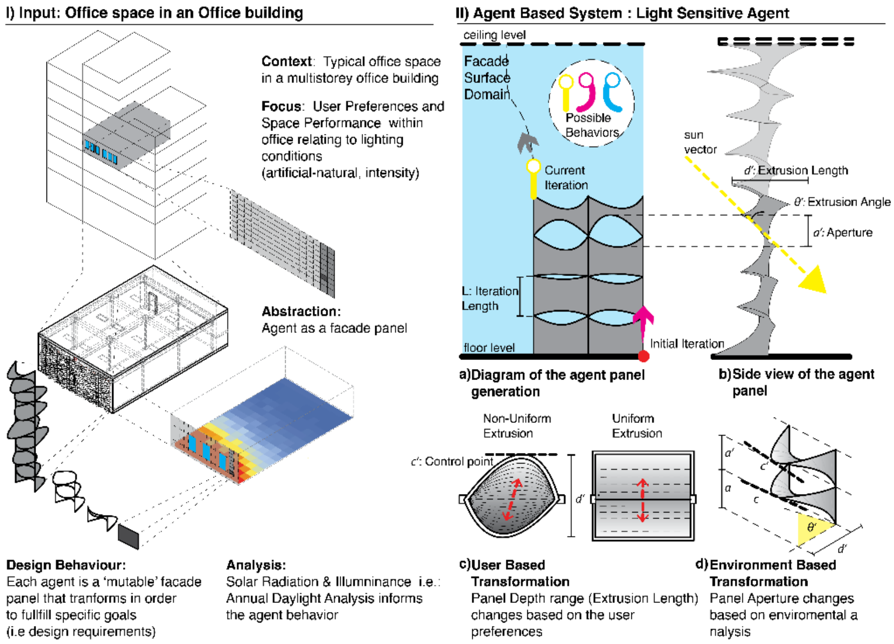

Fig. 3. Diagram illustrating the algorithm and design experiment context for the Light Diffusing Panel Agent.

We are working on the collection of end-users lighting preferences through an IVE system. Such information will be used to inform our MAS system during the design. For example, we can use it as a target for the agent responsible for the creation of the façade panel. More specifically, our agent has a set of probabilities of picking different behaviors while generating the panel described in Section 4.1. Hence, we can search for the best parametrization of these probabilities in order to generate a light profile as close to the user preference as possible. In order to create user profiles, participants have been recruited to measure their most preferred light settings in an office environment given a set of tasks and options. The integration of the IVE into the framework is used in the context of office environments with a direct relationship to building envelopes. So far the data used in the MAS is hypothetical as we are still aggregating the human profile data sets.

4 Experimental Designs

To demonstrate, test, measure and iterate upon the MAS framework a series of experimental designs are pursued. These include: 1) the development of an agent based system for the generation of light diffusing non-structural façade components that aggregate to form a building envelope; 2) the development of an agent based system for the generation of structural components that comprise a form found shell; and 3) the digital to physical prototyping of a one to one form found shell with agent based porosity. Through the synthesis of the experiments the research begins to; analyze the work in progress; point to the successes and failures of the current framework; and begins to draw conclusions on the affordance assumed through their combination as well as necessary refinements.

4.1 Experiment 1: Light diffusing agent based envelope panel

The first experiment investigates the combination of environmental analysis data, specifically solar radiation and luminance, with user preferences for light intensity within an office environment. We are currently implementing a novel algorithm where an agent grows a façade panel according to these two factors. The developed algorithm operates in two stages, as shown in Figure 3. A number of parameters affect the behavior of the agent, which can be set according to user preferences. We plan to derive an automatic configuration of the parameters for the agent design according to the user preference data.

In the first stage of the algorithm, an agent iteratively grows 2D lines in the façade surface through a series of iterations. At each iteration, the agent grows a line of length L from its current position and moves to the end of the newly constructed line. At each iteration, the agent picks one of three different behaviors, which define different types of lines (straight, curved to the right or curved to the left). Each behavior b has a certain probability p_b of being chosen. The agent, however, can switch to a different behavior if the chosen one is invalid such as by creating a line that intersect with others, or that goes beyond the limit of the panel. The agent starts in a corner of the surface and runs for a pre-determined number of iterations, the starting point and iterations are adjustable.

In the second phase, the lines are transformed into 3D surfaces (i.e., linear extrusion), finalizing the realization of the window 'brise soleil.' For the second phase, the user specifies d, the maximum extrusion length; and θ, the maximum extrusion angle. Hence, the lines are not only transformed into 3D surfaces according to a certain length, but also rotate. The actual extrusion length and angle of each line is given by
is a weight defined by the current sun radiation entering the panel in the position of the line. All these aspects affect how the sun light enters the room, changing the illumination inside.

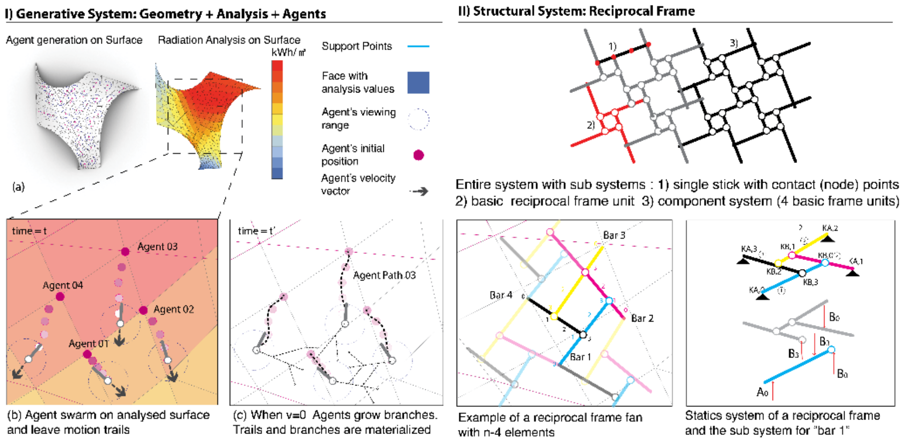

Fig. 4. I) Diagram illustrating the geometry, analysis and agent behavior of our second experiment, II) Constraints and behavior of the reciprocal principle configuration and the statics graph of a frame with 4 elements.

4.2 Experiment 2: Agent Based Thickness of Form Found Shells

In our second experiment, we develop a system of agents to generate structural thickness on zero thickness form found geometries. The objective is to achieve gradient permeability of the structure which allows for enhanced light condition below the structure while minimizing self-weight. Figure 4 (a), (b) and (c) present our initial algorithm. The experiment uses Rhino Grasshopper and two form-finding plugins depending on the type of shell structure. Rhinovault is used for computing compression only surfaces, and Kangaroo for the calculation of tensile surfaces. The Ladybug environmental analysis plugin for Grasshopper is used to measure radiation analysis on and below the generated shells.

The generated geometries are first structurally and environmentally analyzed (Figure 4 (a)). We, then, uniformly distribute a set of agents on the surface. As shown in Figure 4 (b), the agents move while depositing material. The movement of each agent is governed by attraction and repulsion forces, which are weighted based on the environmental and structural analysis (force diagrams). Each agent has a local sensing radius, and it is attracted by its neighbors and the deposited material. Moreover, the agent is influenced by an attraction force towards the initial geometry, thus allowing a user to influence the final shape. Each agent is repelled by the sun radiation, forcing them to avoid areas with high solar radiation values. Therefore, the agents create a structure with openings in the areas of high solar-exposure, allowing the interior of the geometric structure to be well illuminated. The relative weights of these forces are specified by the user. Eventually the agents reach an equilibrium state, where their velocities (v) are close to 0.

The algorithm, then, changes to a different phase, illustrated in Figure 4 (c). Each agent grows geometric "trees", by growing "branches" according to an L-system algorithm. This is executed for two reasons: first, to ensure that the final structure is connected; second, in our next step we plan to use these branches to create reciprocal frames structures (as illustrated in Figure 4 (II)). We consider all agents' paths and branches in a voxelized 3D space. We implement a Marching Cube algorithm and consider each voxel where there is either a deposited material from an agent's path or part of an agent's branch as full (while other voxels are empty), thus generating the final surface [25]. With this final surface we will further explore, through the agents where the non-uniformity is a negotiation of structural efficiency, and the need for porosity based on the environmental conditioning, and user profile preference data.
A final step analyzes the method's success for moving from simulation into analogue physically prototyped shells using rapid 3D printing in SLA with light sensitive resin [9]. Here we implemented a two-step process: step one, the geometry is printed and evaluated using rapid 3D printing; and step two, a part of the geometry is discretized using a technique common in vault construction, Truchet Tiling. This is done in order to examine the construction and assembly process through scaled physical mock-ups.

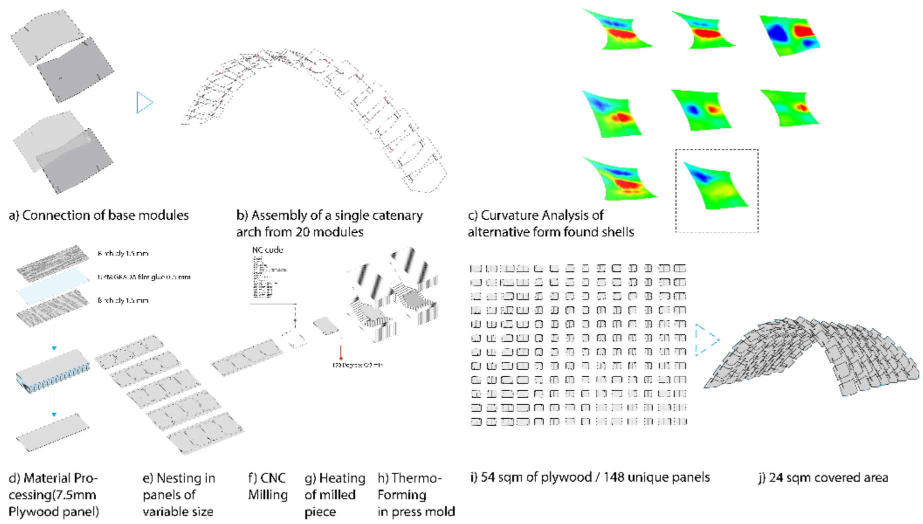

Fig. 5. Diagram illustrating the structural notching (a,b), curvature analysis of the form found shells (c), fabrication process (d-h) and assembly logic of the NEW VIEW pavilion (i,j).

4.3 Experiment 3: Reciprocal frame Structure from Design to Production

In the third case study, illustrated diagrammatically in Figure 5 the research focused on combining structural form finding with an environmentally informed MAS to perforate and articulate reciprocal panels. Our NEW VIEW pavilion experiment is fabricated from and with the design of a modular lightweight funicular shell constructed out of thermo-processed timber elements comprised of curved plywood [30]. The reciprocal element is treated uniquely as a notched panel as opposed to the normative reciprocal stick element. Custom scripts in Grasshopper Kangaroo are implemented for the form finding. The environmental sun radiation analysis was generated using Grasshopper and the ladybug plugin in conjunction with a custom Java (Eclipse and Processing) feedback loop for generating perforation patterns.

The perforation patterns are based on behavior of agents negotiating between environmental sun radiation analysis and formal and structural criteria. The sun radiation analysis (which was performed over a specific time period from 22nd of May to the 22nd of December) informs the trajectory of the agents. Twelve agents per panel are generated and swarm towards surface regions that are less exposed to the sun. Their motion path is inscribed on the panels at given intervals and a simple circular perforation pattern is applied on the panels while trying to maintain the structural integrity of the panel. One hundred parametrically defined and form found shell designs were generated from which ten were further design explored based on the constraints of the reciprocal structure and selected material (1cm curved plywood). A single shell was chosen for final digital fabrication and the optimized environmental articulation. A single shell was chosen for final digital fabrication and the optimized environmental articulation.

5 Results

The results of the experiments to date include quantitative and qualitative observations and measures. As the development of the MAS framework is a work in progress of multiple thrusts the results include general observations for refinement as well as initial empirical data for implementation (environmental, fabrication, structural, and user preference) into the agent designs and algorithms

We start by discussing Experiment 1, where an agent grows a façade panel. The experiment included running daily and annual radiation analysis of 30 different design outcomes of an office space over a specific time-period (9pm-6am) with parametrically varied glazing ratios (20-90%) of the façade. We use the results of a 90% glazing ratio window wall as a baseline, in order to compare it with parametrically designed paneling alternatives and then to results from our agent generated paneling alternatives. Specifically, across these three approaches normative, parametrically tiled, and agent driven generative tiles we measure and compare the following analyses: a) daylight radiation (DLA) in Lux; b) central daylight autonomy (CDA) as a percentage of area with light values above 300 lux; and c) useful daylight illuminance (UDI) as percentage of area with light values between 300 and 800 lux. (See Figure 6).

Figure 6 illustrates that for the same office space our algorithm was able to generate façade panels that provide 14% more area of useful daylight illuminance (UDI) than the 90% glazing ration baseline and 24% more area when compared to the parametric alternative. It also demonstrates a slight decrease to the direct radiation. Hence, our method is at initial reading more energy efficient. Moreover, in comparison with the parametric alternatives, there is an 8% increase of the area that has a Continuous Daylight Autonomy (CDA) for the tested time period (9:00pm -17:00am). As men-

tioned, the proposed approach includes gathering human data for light preferences, from 20 participants that experienced an office space environment through a virtual reality head mounted display (Oculus Rift) and the IVE.
The participants are being asked to adjust the lighting levels through either the blinds for altering the glazing ratio or turning more artificial lights on in order to perform a specific office related activity. As a next step the user preference information will be used to automatically adjust the parameters of our system, allowing a feedback loop that automatically adjusts the system according to the user and the current environment condition.

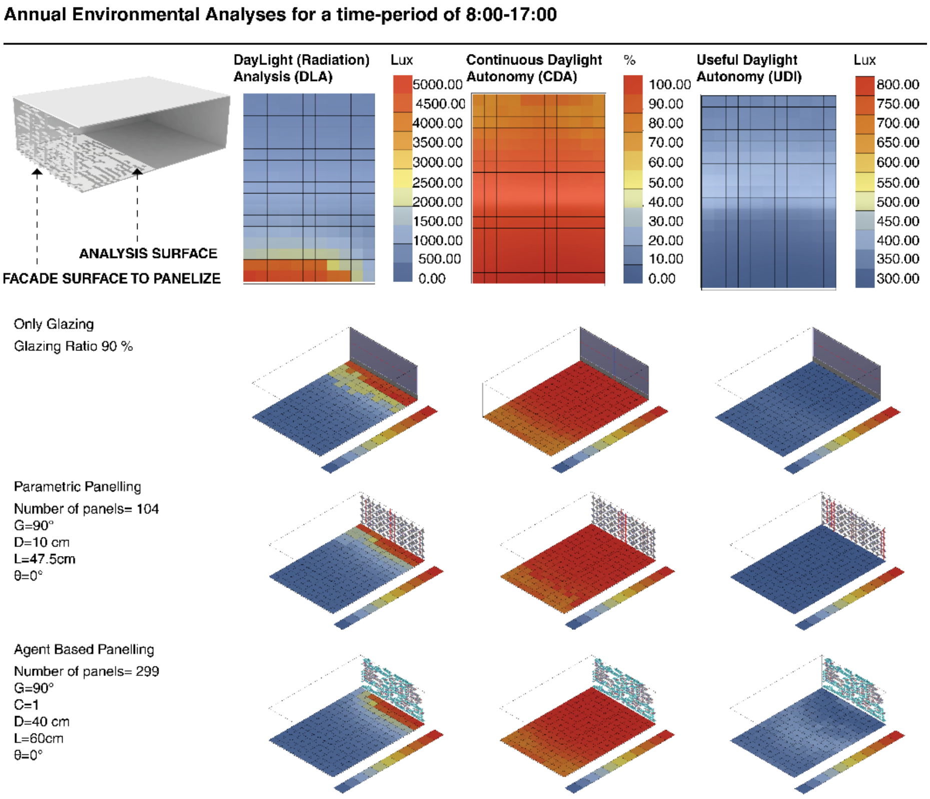

Fig. 6. Illustrates the three design approaches comparatively, normative 90% glazing, to parametrically designed tiles, to that of agent driven generative tiling. The legend on the left describes the design parameters and their values; G is glazing ratio, D is depth of louver or panel, L is length, and θ is rotation angle of the panel or louver. The heat maps show DLA, CDA and UDI analyses for comparison.

We now discuss Experiment 2, where we generate shell structures. Our analysis of the experiment to date includes observations that by implementing a fabrication related discretization to the shell the agents' behavior can be informed by assembly related boundary conditions for each tile. Moreover, by physically simulating and integrating the assembly process, the research investigates how the assembly sequence and related constraints can inform the form finding process and be translated into agent behaviors. One important result to date is an observed limitation of the Marching Cubes algorithm, which is used for the voxelization.

The algorithm provides us with complex and "water-tight" geometries (see Figures 7 and 8) that are suitable for rapid prototyping but are challenging to process with CAM software and hardware. However, we could effectively fabricate the surfaces by 3D printing using our proposed methodology, as shown in Figure 11.

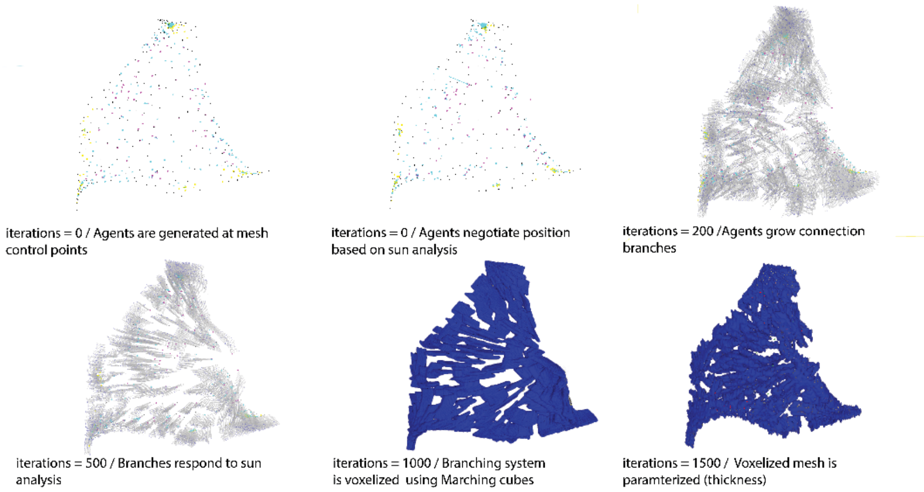

Fig. 7. Illustration of six time steps of the shell MAS interaction where the agents exhibit the reaction to the environmental values, branching and resultant voxelization (i.e. "agent based thickness").

Experiment 3, the NEW VIEW pavilion, served as our initial experiment for developing the MAS design to construction approach. The computational results are the development of the algorithm as illustrated in Figure 9. The fabrication results illustrated in Figure 10 reflect upon the tectonic and a built set of architectural parameters and include the ability to environmentally, more efficiently shade an area 24 sqm with 53 sqm of material. In terms of architectural and constructability performance the free form funicular shell spanning 8 meters, and with 2 support lines was discretized into 148 plywood components totaling 5.4 cubic meters of plywood volumetrically. The reciprocal components, reconceived in a panel format were 1.1cm thick and were thermo-formed for added structural performance. A workforce of 4 skilled people for 2 days was needed for the production of the material and fabrication of the components while 4 unskilled workers were required for the assembly of the pavilion in 2 days [30].

Fig. 8. The illustration presents a sequence of shell structure thickening based on the voxelization (i.e. "agent based thickness"). The resultant thickness and layering of voxels is generatively derived by the MAS from environmental analysis data maps and structural constraints.

The project also provides a qualitative observation of the ability of our agents to inscribe permeability for a complex surface for a particular geography and urban context. While the project did not achieve the fully implemented MAS patterning of the reciprocal components due to cost and time constraints the experiment proved out the workflow for future work. The research also resulted in a number of conclusions for future fabrication procedures, including that the routing of the pattern needs to be performed in the flat stage of each panel prior to pressure and heat forming. Furthermore, the building of the NEW VIEW pavilion highlighted that production related constraints could be implemented as an agent behavior, in addition to the agents' environmental behavior described in Figure 9. Such an additional behavior would account for the critical issue of keeping the material in place when being processed. Specifically in order to avoid breaking the vacuum that holds the piece in place. Future agent behaviors will include avoiding adding perforations on the positions of the air outlets on the CNC table as well as near the edges and joints of the panels. The limitations of the experiment also include the observation that the generative perforation pattern did not prove feasible given the selected fabrication technique of using a 5 axis CNC milling machine, though were achieved and analyzed in simulation.

This was due to the fact that the perforations would distort the fixation of the piece on the cutting table and therefore made the process time consuming and approximately 3 times longer. Another observation is that the agent's path trajectory was informed only from environmental analysis and not synchronously negotiating (i.e., optimizing in a multi-objective fashion with the structural analysis). The form finding and MAS are being developed to work synchronously in future steps. Finally, though the sliding joint facilitated the assembly it proved to be insufficient for providing rigidity to the structure in and of itself.

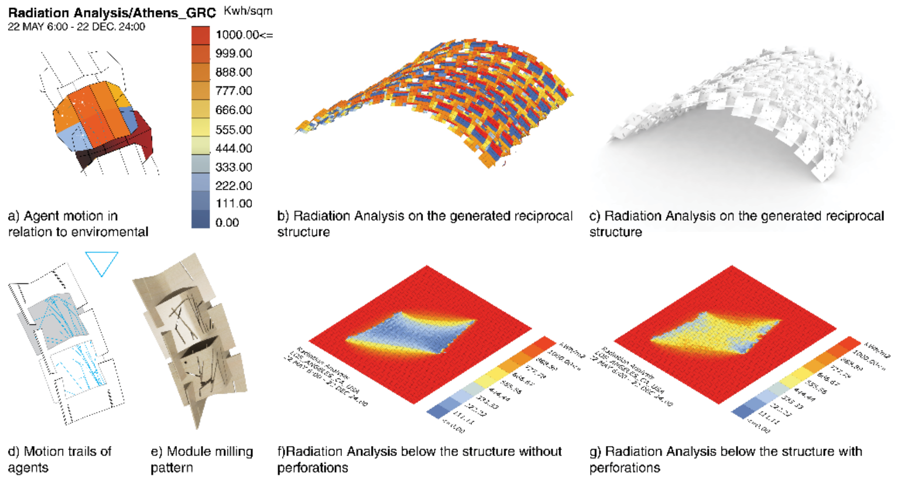

Fig. 9. Diagram illustrating agent motion's path on a reciprocal panel in relation to the environmental radiation analysis (a) and the resulting path and perforation pattern on the panel (d, e) and the whole surface (c). The diagram also illustrates radiation analysis on the whole structure (b) and comparatively the radiation result at the ground of the covered area without the agent based perforations (e) and with it (g).

Fig. 10. Photographs of full vault, detailed joint of reciprocal panel and the final assembly of the NEW VIEW structure in situ on a rooftop in Athens Greece, May 2014.

However, sufficient rigidity is achieved when more than 2 arches were assembled together. The research to date has presented a series of preliminary steps taken towards further testing and proving that an MAS research framework can lead to efficiency in the design to production process as well as to enhance the performance characteristics of geometries that are generatively form found through a combination of environmental, geometric, structural, end user and fabrication objective functions.

6 Discussion and Future work

The research goal is to improve design process and outcomes through an integrated and interdisciplinary MAS approach for architectural design problems. The research aims to provide architectural design teams, enhanced ability to explore forms where geometric intricacy and articulation are intentionally sought after through generative design and emergent patterning. The research questions how un-reduced models such as those generatively created by a MAS can in fact be higher performing and highly complex in terms of material outcomes.

The research takes an interest in the geometric complexity of form found shell structures and complex tiling patterns of façade design for their intrinsic aesthetic qualities, their structural and environmental challenges, and their tectonic and fabrication challenges but as well for their programmatic functionality of work spaces. The reasoning is to be able to improve architects' manage geometric complexity and intricacy, and to integrate emergent and dynamic data sets collected from user behaviors and preferences, which together provide a new kind of *'design agency'*; one based on a closely coupled MAS, cyber physical systems approach.

Our work going forward includes further developing design contexts, agents, and the algorithms that combine the experiments presented. We envision this as a means to benchmark the proposed MAS framework for its ability to provide more optimal results in terms of multi-objective optimization, but equally for the possible effects upon design all the way through to full-scale prototyping and fabrication. As a next step the team will continue; to analyze results of the existing agent designs and algorithms, assess validity and refine; to refine the agent models and combination of the algorithms by testing multiple negotiation and coordination methods; and, in parallel, to find the correct weighting factors and probability distribution functions for making the agents as accurate as possible for all the domains. In that regard, we are continuing to build up a repository of environmental, structural and fabrication analyses as well as user behaviors and preferences. These will in large part help to define the agent tendencies, which in turn enable a feedback between the real world users and simulation of numerous design alternatives, a requisite of design exploration. Future work includes the continued testing and acquiring of the constraints and behavioral definition of the robotics to develop agent behaviors for the fabrication, material, and automated constructions we have presented and envisage.

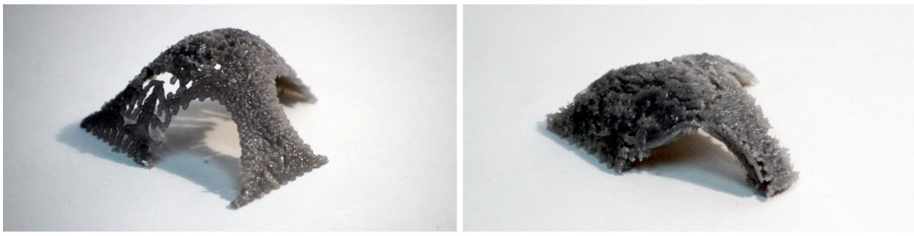

Fig. 11. Photographs of scaled 3D printed resin models representing the physicalized results from MAS.

Specifically, we are developing the framework to accommodate for the form-finding of shell surfaces, where the user will be able define the material and based on that choose either the TNA method for a compression or mesh relaxation for a tensile surface workflow. A stress strain analysis force diagram is being developed to affect the behavior and trajectory of structural agents that operate within the domain of the surface. Refinement of the environmental agent currently informed by the sun analysis will be further enhanced through the collection of user preferences collected through the IVEs. We will continue to test how these agents need to be designed to negotiate their positions in order to optimize light intensity and thermal comfort beneath the structures or inside the building as well as eventually for material embodied energy efficiency. Finally, an agent class will be further developed and implemented in order to cater for the production and robotic assembly constraints. In the subsequent combination of these agents, the MAS will continue to be refined to negotiate the position of the agent at each iteration based on the constraints of the fabrication technique and dimensions of the robot, the structural and environmental objectives, in conjunction with human preferences. At given intervals, all agents will examine the current state of the environment and negotiate to decide their next actions.

We are currently exploring plurality voting, but other negotiation mechanisms may be necessary when agents have different specializations, this is a crucial question and next step for our MAS framework. Work on developing the negotiation and optimization algorithms in close collaboration with our computer science and engineering colleagues will continue. We will add to our metrics of interest questions of accuracy, empirical multi-objective optimization results (as pareto fronts or otherwise), and comparative benchmark, as well as try to measure improvements in terms of design process through the metrics of design cycle latency, solution space size, ease of use and feasibility. Finally, we will continue to ambitiously fabricate the results, as a key motivator of the work is to continue to challenge the opportunities for research at the intersection of cyber (agent simulations), physical (material and robotic agency), and social (human agency) systems, for proving the affordances and limitation of our MAS framework.

Acknowledgements. The work has been supported by grants from Autodesk Inc. and the National Science foundation. This project is partly supported by the National Science Foundation funding under the contract 1231001. Any discussion, procedure, result, and conclusion discussed in this paper are the authors' views and do not reflect the views of the National Science Foundation. We would also like to acknowledge the contributions from Ye Tian, Arsalan Heydarian, and Joao P. Carneiro, Jingbo Yan, Yuze Liu and Rheseok Kim.

References

1. Shell Structures for Architecture: Form Finding and Optimization, ed. S. Adriaenssens, et al., Taylor & Francis - Routledge (2014)
2. Anumba, C., Z. Ren and O. Ugwu: Agents and multi-agent systems in construction, Routledge (2007)
3. Balmond, C. and J. Smith: Informal, ed. C. Brensing, Prestel Verlag (2002)
4. Bhooshan, S. and M. El Sayed: Use of sub-division surfaces in architectural form-finding and procedural modelling, in Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design. Society for Computer Simulation International, 60-67, Boston, Massachusetts (2011)

5. Block, P. and J. Ochsendorf: Thrust network analysis: A new methodology for three-dimensional equilibrium: International Association for Shell and Spatial Structures, 155, p. 167 (2007)
6. Braumann, J. and S. Brell-Cokcan: Parametric Robot Control: Integrated CAD/CAM for architectural design, in ACADIA 11: Integration through computation. 242-251, Calgary/ Banff (2011)
7. Bullinger, H.-J., W. Bauer, G. Wenzel and R. Blach: Towards user centred design (UCD) in architecture based on immersive virtual environments: Computers in Industry, 61(4), p. 372-379 (2010)
8. Burry, J., M. Burry, M. Tamke, M.R. Thomsen, P. Ayres, A.P. Leon, D. Davis, A. Deleuran, S. Nielson, and J. Riiber: Process Through Practice: Synthesizing a Novel Design and Production Ecology, in ACADIA 12: Synthetic Digital Ecologies. 127-138, San francisco (2012)
9. Chandru, V., S. Manohar and C.E. Prakash: Voxel-based modeling for layered manufacturing: Computer Graphics and Applications, IEEE, 15(6), p. 42-47 (1995)
10. Chilton, J. and H. Isler: Heinz isler. The Engineer's Contribution to Contemporary Architecture, London, Thomas Telford Publishing 168 (2000)
11. DeLoach, S.A., M.F. Wood and C.H. Sparkman: Multiagent systems engineering: International Journal of Software Engineering and Knowledge Engineering, 11(03), p. 231-258 (2001)
12. Evans, R.: The projective cast: architecture and its three geometries, Cambridge,MA, MIT press (2000)
13. Fabian Scheurer, C.S., Markus Braach: From design to production: Three complex structures materialised in wood, in 6th International Conference Generative Art Milan, Italy (2005)
14. Fallacara, G.: Digital stereotomy and topological transformations: reasoning about shape building, in Proceedings of second international congress construction history, Queen’s College Cambridge, Cambridge. 1075-1092, (2006)
15. Gerber, D.J.: Paradigms in Computing: Making, Machines, and Models for Design Agency in Architecture, ed. D.J. Gerber and M. Ibanez, Los Angeles, CA, eVolo (2014)
16. Gerber, D.J.: The Parametric Affect: Computation, Innovation and Models for Design Exploration in Contemporary Architectural Practice, in Graduate School of Design (GSD), GSD, Cambridge (2009)
17. Gramazio, F. and M. Kohler: Digital materiality in architecture, Vol. 1. Baden, Lars Müller Publishers, 111 (2008)
18. Heydarian, A., J.P. Carneiro, D.J. Gerber, B. Becerik-Gerber, T. Hayes, and W. Wood: Immersive Virtual Environments: Experiments on Impacting Design and Human Building Interaction, in Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA): Rethinking Comprehensive Design: Speculative Counterculture. 729–738, Kyoto, Japan (2014)
19. Hoes, P., J.L.M. Hensen, M.G.L.C. Loomans, B. De Vries and D. Bourgeois: User behavior in whole building simulation: Energy and Buildings, 41(3), p. 295-302 (2009)
20. Kaczynski, M.P., W. McGee and D. Pigram: Robotically Fabricated Thin-shell Vaulting: A method for the integration of multi-axis fabrication processes with algorithmic form-finding techniques, in ACADIA 11: Integration through Computation. 114-121, Banff, Alberta (2011)
21. Kilian, A. and J. Ochsendorf: Particle spring systems for structural form finding: Journal of the international association for shell and spatial structures: IASS, 46(147) (2005)
22. Lachauer, L., M. Rippmann and P. Block: Form Finding to Fabrication: A digital design process for masonry vaults: Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, (2010)
23. Larsen, O.P.: Reciprocal Frame Architecture, Elsevier (2008)

24. Lin, S.-H.E. and D.J. Gerber: Designing-in performance: A framework for evolutionary energy performance feedback in early stage design: Automation in Construction, 38, p. 59-73 (2014)
25. Lorensen, W.E. and H.E. Cline: Marching cubes: A high resolution 3D surface construction algorithm, in ACM siggraph computer graphics. ACM, 163-169, (1987)
26. Maher, A. and M. Burry: The Parametric Bridge: connecting digital design techniques in architecture and engineering, in ACADIA 03: Crossroads of Digital Discourse. 39-47, Indianapolis, Indiana (2003)
27. Marcolino, L.S., E. Pantazis, B. Kolev, S. Price, Y. Tian, D. Gerber, and M. Tambe: Agents vote for the environment: Designing energy-efficient architecture, in AAAI Workshop on Computational Sustainability (AAAI 2015). Texas, USA (2015)
28. Marcolino, L.S., H. Xu, A.X. Jiang, M. Tambe and E. Bowring: Team Formation in Large Action Spaces, in 17th International Workshop on Coordination, Organisations, Institutions and Norms (COIN 2014). Paris, France, (2014)
29. Menges, A.: Morphospaces of Robotic Fabrication, in *Rob| Arch 2012*, S. Brell-Cokcan and J. Braumann, Editors., Springer, Vienna, p. 28-47 (2013)
30. Pantazis, E. and D.J. Gerber: Material Swarm Articulations - New View Reciprocal Frame Canopy, in 32nd eCaade: Fusion. E.M. Thompson, 463-473, Newcastle, England (2014)
31. Piker, D.: Kangaroo: form finding with computational physics: Architectural Design, 83(2), p. 136-137 (2013)
32. Pine, B.J.: Mass customization: the new frontier in business competition, Cambridge, MA, Harvard Business Press (1999)
33. Pottmann, H., M. Eigensatz, A. Vaxman and J. Wallner: Architectural geometry: Computers & Graphics, 47, p. 145-164 (2015)
34. Pugnale, A., D. Parigi, P.H. Kirkegaard and M. Sassone: The principle of structural reciprocity: history, properties and design issues, in IABSE-IASS Symposium- Taller, Longer, Lighter: meeting growing demand with limited resource. Hemming Group Ltd., London (2011)
35. Reinhart, C.F.: Lightswitch-2002: a model for manual and automated control of electric lighting and blinds: Solar Energy, 77(1), p. 15-28 (2004)
36. Reynolds, C.W.: Flocks, herds and schools: A distributed behavioral model: ACM Siggraph Computer Graphics, 21(4), p. 25-34 (1987)
37. Rippmann, M. and P. Block: Digital Stereotomy: Voussoir geometry for freeform masonry-like vaults informed by structural and fabrication constraints: Proceedings of the IABSE-IASS symposium, (2011)
38. Rippmann, M., L. Lachauer and P. Block: Interactive vault design: International Journal of Space Structures, 27(4), p. 219-230 (2012)
39. Schumacher, P.: Parametric Order – Architectural Order via an Agent Based Parametric Semiology. Adaptive Ecologies – Correlated Systems of Living, ed. T. Spyropoulos, London, AA Publication (2012)
40. Sycara, K.P.: Multiagent systems: AI magazine, 19(2), p. 79-92 (1998)
41. Tachi, T. and G. Epps: Designing One-DOF Mechanisms for Architecture by Rationalizing Curved Folding, in Proceedings of the International Symposium on Algorithmic Design for Architecture and Urban Design (ALGODE). Tokyo, Japan (2011)
42. Terzidis, K.: Algorithmic architecture, Oxford, Burlington, MA, Architectural Press (2006)
43. Van Mele, T., L. Lachauer, M. Rippmann and P. Block: Geometry-based understanding of structures: Journal of the International Association of Shell and Spatial Structures, 53(4), p. 285-295 (2012)
44. Weinstock, M. and N. Stathopoulos: Advanced simulation in design: Architectural design, 76, p. 54-59 (2006)
45. Wooldridge, M.: An Introduction to Multiagent Systems, 1 ed, Glasgow, UK, John Wiley & Sons, 453 (2009)