

A Multi Agent Systems for Design Simulation Framework: Experiments with Virtual Physical Social Feedback for Architecture

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ABSTRACT

This paper presents research on the development of multi-agent systems (MAS) for integrated and performance driven architectural design. It presents the development of a simulation framework that bridges architecture and engineering, through a series of multi-agent based experiments. The research is motivated to combine multiple design agencies into a system for managing and optimizing architectural form, across multiple objectives and contexts. The research anticipates the incorporation of feedback from real world human behavior and user preferences with physics based structural form finding and environmental analysis data. The framework is a multi-agent system that provides design teams with informed design solutions, which simultaneously optimize and satisfy competing design objectives. The initial results for building structures are measured in terms of the level of lighting improvements and qualitatively in geometric terms. Critical to the research is the elaboration of the system and the feedback loops that are possible when using the multi-agent systems approach.

Keywords

Generative Design; Parametric Design; Multi-Agent Systems; Architecture; Multi-disciplinary Design Optimization; Immersive Virtual Reality; Design Performance.

INTRODUCTION

The rapid evolution of computational design tools such as associative parametric modeling [1], algorithmic and generative design methods [2], and multi-disciplinary design optimization methods have provided designers with a new set of design exploration possibilities that can aid them to

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actively collaborate with other disciplines and to more rapidly explore design alternatives, and manage the complexity of design problems inclusive of human, environmental and structural feedback loops [3]. As part of this rapid industry evolution simulations are used increasingly in design practices for evaluating different performance aspects of a design including for factors such as risk, cost, energy, structural efficiency, lighting, and social utility [4].

Our work situates itself amongst a body of research that investigates the applicability of Multi-Agent Systems (MAS) in architectural design, building engineering and construction [5-7]. It proposes an integrated approach for architectural design where agent-based algorithms are researched for their ability in simulation to negotiate across multiple design objectives including geometry, material properties, fabrication constraints, environmental factors and human preferences. This approach attempts to go beyond the limitations of current computational design techniques that are restricted to either simple parameter sets or single optimization strategies. One main objective of our work is to investigate the applicability of a custom MAS framework for the design of building components and structures which challenge and enhance the existing capabilities of Multi-disciplinary Design Optimization (MDO) and MAS methods. The proposed approach combines design data, optimization routines and analysis with real time data collected from users where the MAS is conceived not purely as a swarm or flock. Furthermore, we aim at extending the capabilities of MDO which can often be limited to pre-determined and top down driven solution spaces with simple geometries and similarly simple optimizations based on reduced analysis and objectives.

The research seeks to test the hypothesis that the MAS framework will lead to informed design variation and solution spaces that are larger and pre-optimized where geometric and performance complexity are not marginalized nor simplified. The multiple inputs and datasets from performance analysis, illustrated in Figure 1, are used for the design of specific agent behaviors that compose an integrated design system for design with increasingly large and

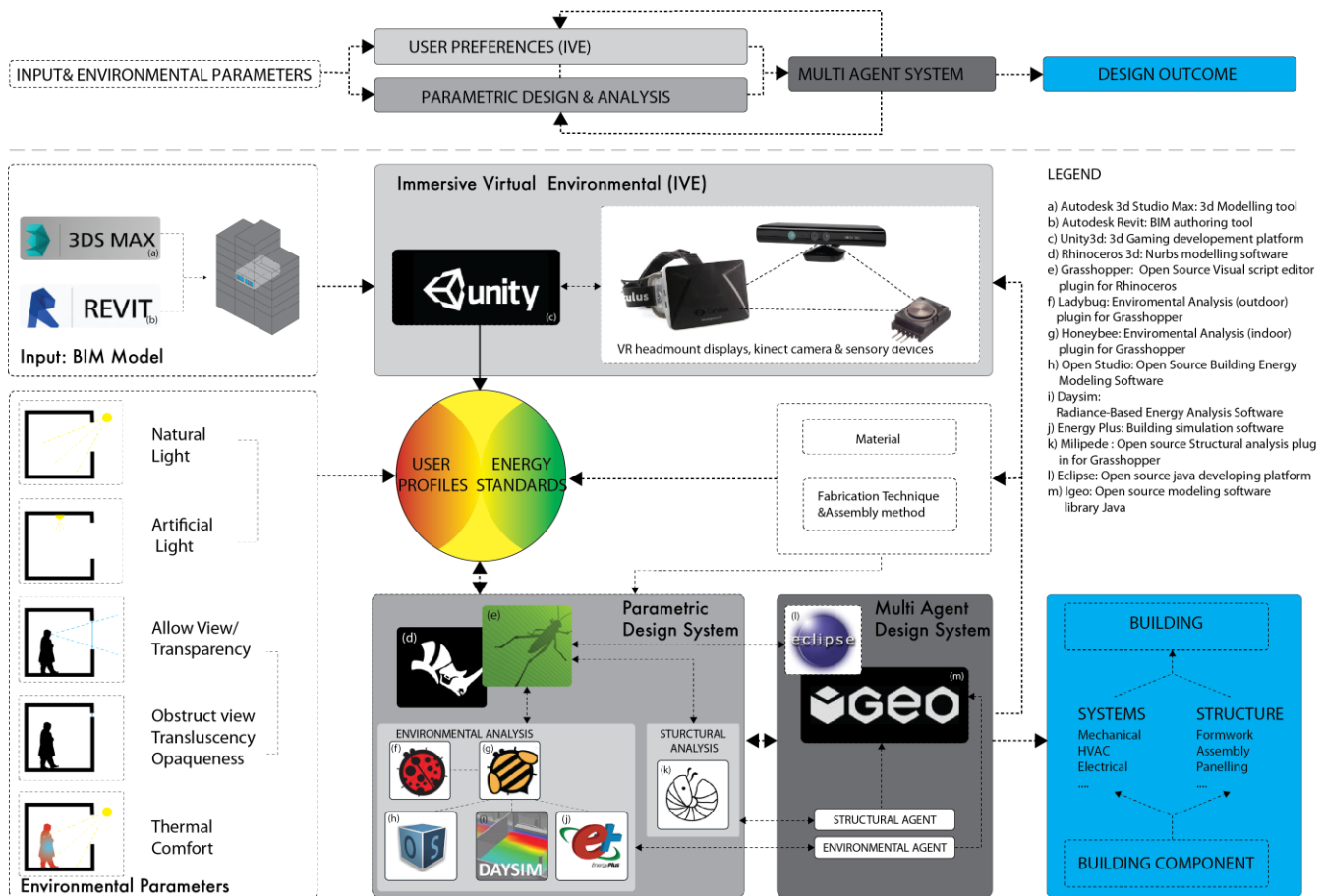


Figure 1: Overview of the proposed Multi Agent Design Framework. The diagram illustrates the geometry and environmental inputs and parameters, the linking of the digital to physical environments, the analysis engines, and the agent IDE.

complex set of design objectives. These include virtual, physical, and social objectives in conjunction with structural and constructability parameters. As the use of simulation for form finding and optimizing geometry is rapidly becoming a common practice in architectural design it is an essential component of our process [8]. One key innovation of the research, seen in Figures 1 and 2, is that it bridges the virtual-physical divide through the linking of the MAS to an immersive virtual environment (IVE). An IVE setup is used to collect user data that enhance the agents' behaviors. Another key innovation of the research is the learning from computer science social choice and voting techniques in addition to flocking behaviors of the agents in order to improve upon design products and decision making processes [9]. The paper presents the state of development and testing of our MAS for design framework as well as the initial experimental results and next steps. The paper provides background and literature review as a means to highlight initial gaps and analysis. The experimental design and results presented include: 1) the development of the MAS for simulating a light diffusing building component that takes into account environmental analysis as well as user data; and 2) a second scenario where agents, guided by

environmental analysis, emerge a geometric structure. The paper lastly enumerates a research plan and next steps for the incorporation of an expanded set of architectural, geometric, and social objectives experimentally.

BACKGROUND & REVIEW

An overview of MAS in architecture and engineering, are described in brief highlighting the limited and nascent nature of the field. Secondly, given our research methodology an introduction into the use of Immersive Virtual Environments (IVE) in the fields of architecture, engineering and simulation for design decision-making is described. Third we relate our current work back to research on Multi-disciplinary Design Optimization (MDO) and finally highlight the gaps in need of addressing.

Multi-Agent Design Systems

Multi-Agent Systems (MAS) have generated a growing number of experimentalists in architecture in recent years [10]. These include researchers, units, and practitioners such as Cecil Balmond, Achim Menges, and RMIT in Australia as

well as practices such as at Zaha Hadid Architects [11]. These approaches are arguably becoming a new paradigm for conceptualizing design, exploring design solution spaces more efficiently and for solving complex problems [12]. Much of this development in architecture has originated from the seminal work of Craig Reynolds [13]. The introduction of MAS in architectural design is albeit relatively new and has focused mostly on a specific type of agent algorithm known for being able to generate complex self-organizing geometry.

Thus behavioral design methodologies such as an MAS framework enable a shift from the direct invention of form or organization to intensive intrinsic, bottom up, collectively intelligent processes for exploring morphology and the generation of form and lastly optimization and rationalization for performance criteria and constructability [14].

Different studies have identified the applicability of MAS in different stages of the architectural process but in aggregate illustrate a noticeable gap: the majority of the precedent work has been limited by investigating only specific behavioral models such as Reynolds' flocking. As a result these precedents also highlight a focusing mostly on the generative and formal aspects of the simulations and not on the impacts of performance criteria nor on the incorporation of human and real world data for informing the simulation behavior.

Our work couples simulation environment agents (the virtual) with material systems (the physical) with human agency (the social) through bringing to the agent algorithms some exposure to social choice and voting based Artificial Intelligence (AI) techniques. This occurs through an accumulation of real world behavior both from human and environmental and physics based sources which are then feedback into the agent probability distribution functions (PDFs) discussed in later sections.



Figure 2: Example of participant navigating an Immersive Virtual Environment (IVE) with a head-mounted display.

Immersive Virtual Environments

The second area of precedent research relates to an invention of our design methodology, the incorporation of human data to inform our MAS in conjunction with a version of rules defined by Reynolds. Immersive Virtual Environments (IVE) have been brought to the design research for both practical reasons of enabling more expansive and cost effective data capture and experimentation but equally as a means to develop iterative feedback for machine learning across the virtual physical social divides. There is significant research to date on informing agents through human data in the domains of security, economics and game theory but little work has been done in the arena of design exploration or architectural performance [15, 16]. Some of our previous research has suggested not only that participants perform similarly within IVE as they do in physical environments, but they also feel similar feelings of presence within such environments [17]. The IVE allow the design researcher to control for all potentially confounding variables and to properly isolate the variables of interest for measuring statistical variance and significance. Prior research has also demonstrated that participants often try to act in a "virtuous" way in front of an experimenter [18]. In studying social behavior research usually starts with inputs and assumptions from real-world settings including human tendencies, contextual data, and the complex interactions allowing for simulation outputs which can be analyzed iteratively and in a feedback loop within the MAS framework. Further background in the development and use of IVE's for design alternative and human preferences can be found at [17, 19].

Multi-Objective Design Optimization

A third area of background is that of our previous and continuing research into the combining of associative parametric design models and the automation of performance driven solution space generation and ranking. In previous work we have illustrated the value of harnessing high performance computing and cloud based procedures to generate expansive solution spaces while simultaneously optimizing across aligning and contradicting objective functions [20]. However our MDO research to date works in isolation from human centered inputs and is only generative within a predetermined solution space [21]. One hypothesis is that simulation can be improved by the combining of MDO research with that of the MAS framework once informed by the capturing of user data from IVEs in conjunction with MAS approaches incorporative of social choice. It is evident in the literature and contemporary discourse that interest into MAS approaches in architecture is growing. However it is also clear that there are few precedents to illustrate the development of MAS techniques beyond simple flocking algorithms within architecture. While there is incredible development in computer science of agents they have yet to trickle down to the design field. Our work uniquely is learning from social choice based MAS

for architectural design decision making [9]. Furthermore what is also evident is that the use of agents considering performance criteria beyond material and geometric aspects remains in a very nascent state.

Related work in the fields of design, with few exceptions, has shown interest mostly for the generation of geometric complexity and less for addressing design problems holistically and requisite of environmental and human factors. Our research methodology and resultant framework is in part a response to these identified gaps: 1) the lack of sophistication of the agent models in use in architecture; 2) the lack of existing MAS to negotiate highly coupled and complex multi-objective design scenarios; and 3) the lack of linkage and crossing of the virtual physical social systems and data sources.

RESEARCH METHOD & EXPERIMENTAL DESIGNS

The objective is to evaluate whether the proposed MAS design framework can provide designers with an alternative design approach that incorporates bottom up strategies and data for informing agents that optimize architectural designs. This work attempts to develop a versatile and extensible MAS that supports and synthesizes environmental, structural, and user agencies by linking interdependent agent based sub-models into a MAS. Hence, our framework assumes multiple levels of agency. We are working towards agent classes, each responsible for different design requirements. In this paper we present two classes: one responsible for creating a window panel that controls the amount of light that enters a room; and another responsible for generating a shell structure with different degrees of porosity that allow the direct radiation of sun light under the structure. The creation of more agent classes and the definition of how exactly these classes will interconnect and negotiate multiple aspects of design are our next steps into implementing this framework. We are currently exploring voting as a negotiation mechanism, as presented at [9]. Due to space constraints, in this paper we focus on the definition of two agent classes.

Our proposed agent classes are based on agents with locally defined rule sets that emerge into global form using a bottom-up approach. Such shape is within a larger context of an assembly, and can be measured according to well-defined performance criteria. Performance criteria include and anticipate environmental, structural and material constraints as well as user preferences. These performance criteria obtain different weighting factors depending on the type and scale of the design space, or the preferences of the designer.

Our algorithms currently use sun radiation analysis data to inform the agents while generating a surface. They can also be parameterized, in order to attend preferences of a user concerning the amount of light inside a room. We are currently using an IVE system to directly obtain a user's

preference. Such information can then be used to dynamically adapt and change the surfaces in our proposed framework, by changing the algorithms parameters accordingly, but this feedback loop is still under implementation. We now proceed to explain the two agent classes, and in the next section we show our experimental results.

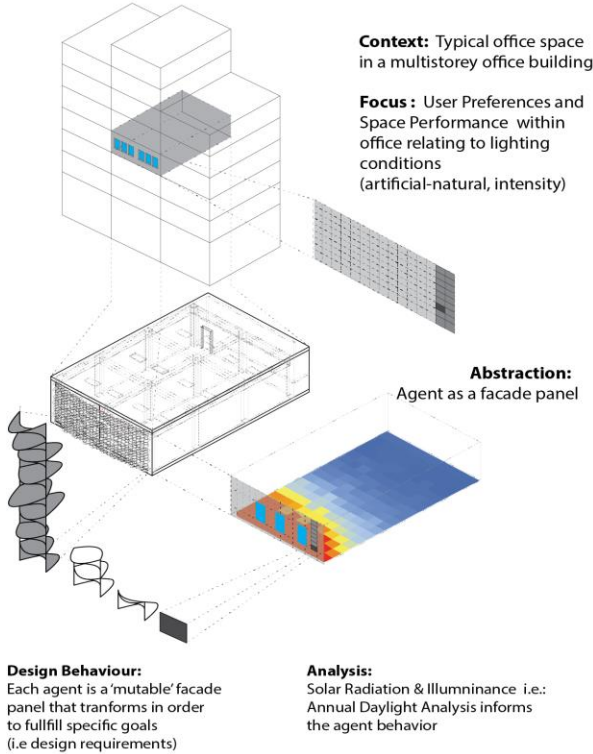
Experiment 1: Agent 1.1 Light diffusing Panel Agent

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 working in a novel algorithm where an agent grows a window panel according to these two factors.

The developed algorithm has two phases to date. In the first phase, an agent iteratively grows 2d lines in the panel surface. In the second phase, the lines are transformed into 3d surfaces (i.e., linear extrusion), finalizing the realization of the window panel. A number of parameters affect the behavior of the agent, which can be set according to the user preferences. For the first phase, the parameters are: L , which defines the length of each line; p_1, p_2, p_3 , the probabilities of each agent behavior (which is clarified further below). 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. All these aspects affect how the sun light enters the room, changing the illumination inside.

We now explain our algorithm in detail. Figure 3 (a) shows the first phase. The agent starts in a corner of the panel, and performs a series of iterations. At each iteration, the agent grows one line from its current position, and moves to the end of that new line. The agent can grow three different types of lines, according to three different behaviors: straight, left-curved or right-curved, as shown in the figure. In the beginning of each iteration, the agent picks its next behavior randomly, according to the probabilities p_1, p_2 and p_3 . However, the agent must also obey two constraints: the new line must not intersect a previously constructed line and the agent must not leave the boundaries of the given surface. If the randomly chosen behavior would violate these constraints, a new behavior is selected until valid. More specifically, the agent checks the history of all previous selected behaviors and changes to the behavior that has the ratio furthest away from the desired one according to the probabilities p_1, p_2 and p_3 (which naturally induce a ratio). This phase terminates after a pre-specified number of iterations. In the second phase, shown in Figure 3 (b), (c) and (d), the lines are extruded in 3d geometries. For each line, a length and angulation are chosen according to the following equations: $d' = d * w$; $\theta' = \theta * w$, where $0 \leq w \leq 1$ is a weight given by the current sun radiation entering the panel in the position of the line.

Input: Office space in an Office building



Hence, each line will have a different d' and θ' , but bounded by the preference of the user. Moreover, the user can specify two different types of extrusion: uniform or non-uniform (Figure 3 (b)). The uniform case follows as just described, while in the non-uniform case the user can also specify a “control point”, which affects the degree of the curves, which generate the surface as shown in the figure. Finally, these parameters define the aperture a' between surfaces (Figure 3(d)), which in turn influences the amount and type of light that enters the space.

Experiment 2: Agent 2.1 Reciprocal frame porosity Agent

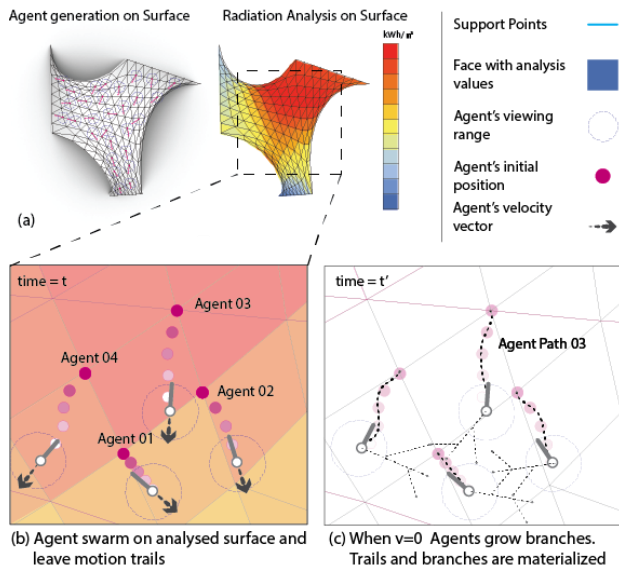
In our second experiment, we are going towards a system of agents that grow a geometric structure. The idea is to allow porosities in the structure which serves as apertures for sun light. Figure 4 (a), (b) and (c) present our initial algorithm. We start with an initial form found geometry (that is generated with a mesh relaxation algorithm) input by a user. This geometry is then analyzed to obtain the amount of sun radiation on the surface (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. 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 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)). Finally, we consider all agents’ paths and branches in a voxelized 3d space. We 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. With this final surface we then expect to further explore, through the agents self-organizing reciprocal frames 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.

Figure 3: Diagram showing the algorithm of the Light Diffusing Panel Agent.

I) Generative System: Geometry + Agents + Analysis



II) Structural System: Reciprocal Frame

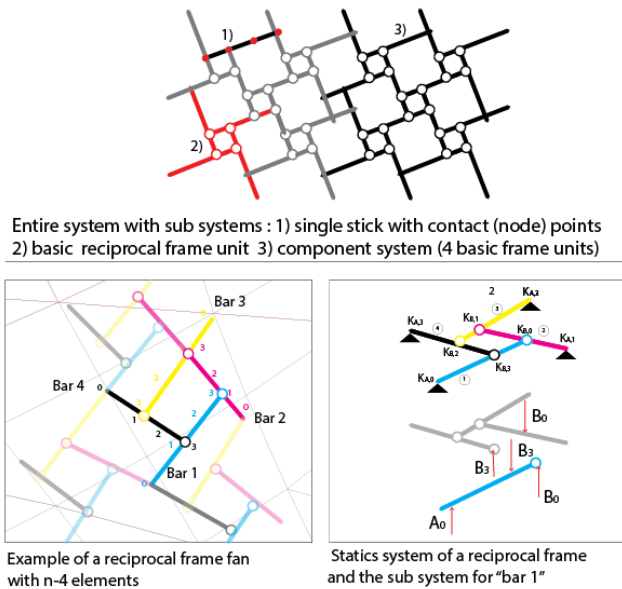


Figure 4: I) Diagram illustrating the geometry, analysis and agent behavior of our second experiment, II) Constraints and behavior of the reciprocal principle configuration and the statics graph of a frame with $n=4$ sticks.

RESULTS & ANALYSIS

The initial results of our experiments serve as a proof of concept for the proposed framework. We start by discussing Experiment 1, where an agent grows a window 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 (Figure 5 (a)).

We use these results as a baseline, in order to compare with our agent class. Specifically, each analysis measured: a) daylight factor (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.

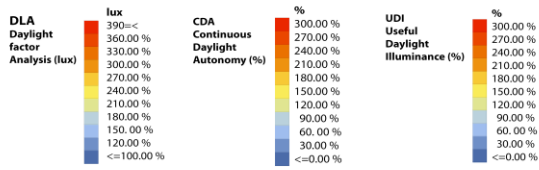
We then run our agent system to generate window panels for the same office space. We test 25 different parametrizations of our algorithm, and in Figure 5 (b) we show the results of a subset of those. As can be seen, our algorithm was able to generate façade panels that provide the same amount of useful daylight illuminance as the baseline, but critically while bringing down the direct radiation. Hence, our method is more energy efficient. Moreover, in comparison with the baseline, there is a 5% increase of the area that has a Continuous Daylight Autonomy for the tested time period (9:00pm -17:00am). Selected design outcomes, expressive of our desired geometric intricacy, can be seen in Figure 6 (a). The research also included 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 were 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 (see Figure 2). 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.

Finally, Figure 6 (b) shows our initial results for Experiment 2, where a swarm of agents emerge a shell structure with permeability that allow the direct radiation of sun light. The figure shows the geometric variations and complexity that can be obtained by different parametrizations of our algorithm, allowing a user to then choose according to her preferences with greater understanding of the performance of the structure. The evaluation of the performance of these designs in terms of DLA, CDA and UDI is still work-in-progress.

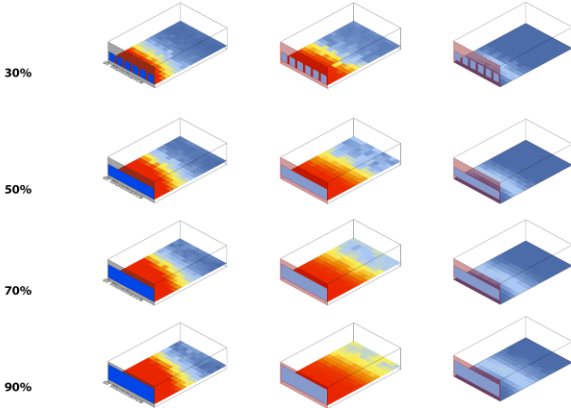
DISCUSSION AND FUTURE WORK

For the two experiments, we explicitly selected two different approaches for developing the MAS in order to observe differences in the implementation of tools, and in the evaluation of the design alternatives that the system provides across two objectives: geometric intricacy and design performance (in terms of measurable illumination performance). Our next immediate step is to introduce a feedback loop for both agent classes proposed, allowing the human preferences to directly influence the design outcome. User preference data sets are currently being collected to include not only lighting levels but also heat, sound/noise and viewing preferences.

Annual Environmental Analyses for a time-period of 8:00-17:00



Glazing ratio



Agent Based Paneling

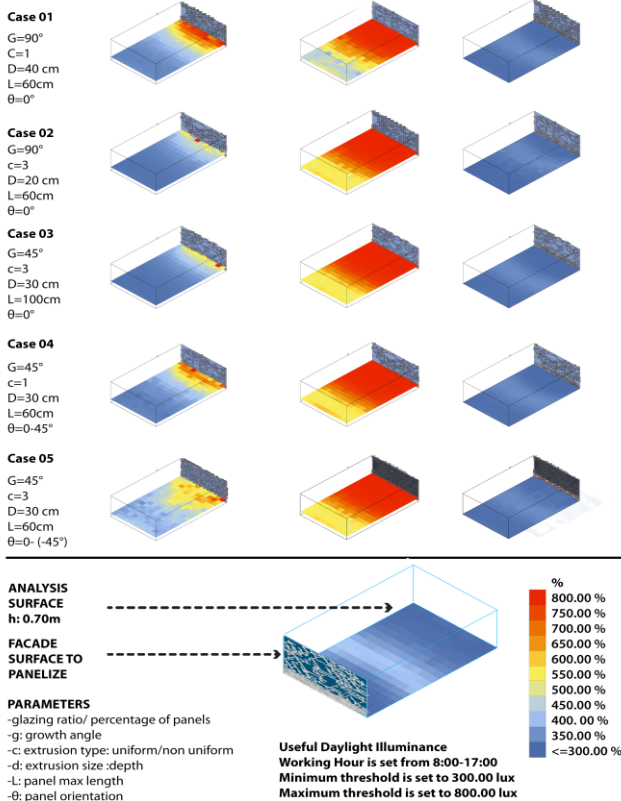


Figure 5: DLA, CDA and UDI analysis with variable glazing ratios and agent generated panels for 5 cases where panel patterns vary for differing percentages and connections of horizontal and vertical lengths, angles and extrusion depths.

Concerning our second agent class, which builds a shell structure with gradient porosity, we are currently exploring how to use the output of our algorithm to build reciprocal frames (in order to realize the proposed structures). In particular, using the branches (L-systems) constructed by the agents is our current means to guide the construction of the reciprocal frames. At this stage the quantitative evaluation of the algorithm results is still a work in progress. In addition, materializing the results of both agent classes at varying scales, in order to further empirically test the design outcomes is currently being developed through 3d printing experiments.

Finally, while in this paper we presented two agent classes, our vision is an integrated multi-agent framework where many agents negotiate across multiple aspects of design. Therefore, as next steps towards fully implementing the frameworks' vision, more agent classes must be implemented, and the actual negotiation and coordination mechanisms must be defined, refined and evaluated. As mentioned, we are currently exploring voting mechanisms for architectural and performance objectives in building design [9].

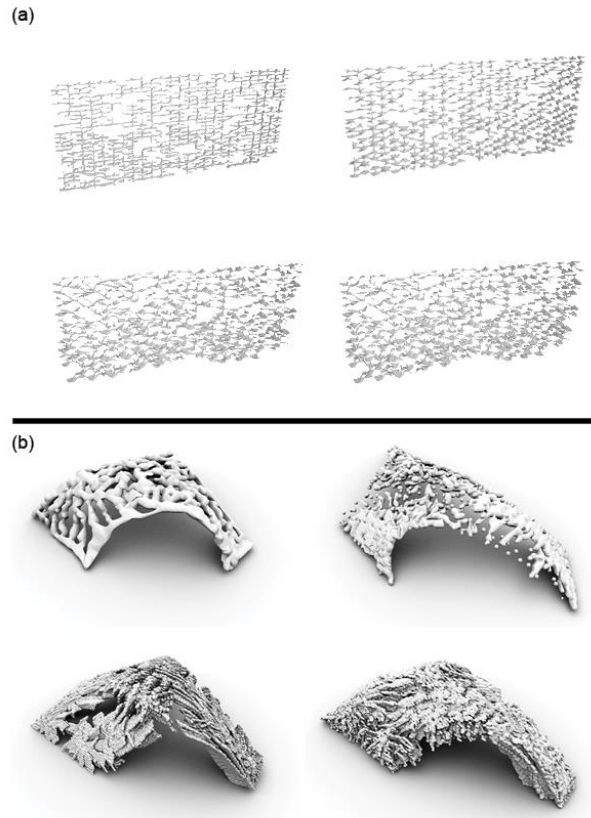


Figure 6: A sub-set of design variations from experiment 1 (a) and experiment 2 (b) generated by the MAS for design framework based on environmental performance analysis values.

In conclusion, we would suggest that the research as a whole is contributing to a greater understanding of the myriad of optimization and MAS techniques being deployed, in design and architectural research. Uniquely the work will continue to argue for the crossing of the virtual, physical, and social divides as a means to inform the agent based simulations with environmental, structural and user preference data, driving our design processes toward managing real world complexities.

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REFERENCES

1. Gerber, D.J., *The parametric affect: Computation, innovation and models for design exploration in contemporary architectural practice*. 2009, Cambridge: Harvard University Graduate School of Design. 244.
2. Terzidis, K., *Algorithmic architecture*. 2006, Oxford ;Burlington, MA: Architectural Press.
3. Gerber, D.J., *Parametric practices: Models for design exploration in architecture*. 2007, Harvard University Graduate School of Design: Cambridge.
4. Yi, Y.K. and A.M. Malkawi, *Optimizing building form for energy performance based on hierarchical geometry relation*. Automation in Construction, 2009. **18**(6): p. 825-833.
5. Anumba, C.J., et al., *Intelligent Agent Applications in Construction Engineering, Creative Systems in Structural and Construction Engineering*. 2001: CRC Press.
6. Beetz, J., J. Van Leeuwen, and B. De Vries, *Towards a Multi Agent System for the Support of Collaborative Design*. 2004, Developments in Design & Decision Support Systems in Architecture and Urban Planning, Eindhoven: Eindhoven University of Technology.
7. Leach, N., *Swarm Urbanism*. Architectural design, 2009. **79**: p. 56-63.
8. Kilian, A. and J. Ochsendorf, *Particle-Springs Systems for Structural Form Finding*. Journal of the International Association for Shell and Spatial Structures, 2005. **Vol. 46**(147).
9. Marcolino, L.S., et al., *Agents vote for the environment: Designing energy-efficient architecture*, in *AAAI Workshop on Computational Sustainability*. 2015: Texas.
10. Gerber, D.J. and M. Ibanez, *Paradigms in Computing: Making, Machines, and Models for Design Agency in Architecture*. 1 ed. 2014, Los Angeles: eVolo.
11. Schumacher, P., *The autopoiesis of architecture*. 2011, Chichester: J. Wiley.
12. Jennings, N.R., K. Sycara, and M. Wooldridge, *A roadmap of agent research and development*. Autonomous agents and multi-agent systems, 1998. **1**(1): p. 7-38.
13. Reynolds, C., *Flocks, Herds, and Schools*. ACM SIGGRAPH, 1987.
14. Menges, A., *Morphospaces of Robotic Fabrication*, in *Rob/ Arch 2012*. 2013, Springer: Vienna. p. 28-47.
15. Kalay, Y.E., *Performance-based design*. Automation in construction, 1999. **8**(4): p. 395-409.
16. Simeone, D., et al. *Modelling and Simulating Use Processes in Buildings*. in *eCAADe 2013: Computation and Performance*. 2013. Delft, The Netherlands: Faculty of Architecture, Delft University of Technology; eCAADe (Education and research in Computer Aided Architectural Design in Europe).
17. Heydarian, A., et al., *Immersive Virtual Environments: Experiments on Impacting Design and Human Building Interaction*, in *Rethinking Comprehensive Design: Speculative Counterculture, Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRRIA)*. 2014: . p. 729-738.
18. Boyce, P.R., *Human factors in lighting*. 2014: Crc Press.
19. An, L., *Modeling human decisions in coupled human and natural systems: Review of agent-based models*. Ecological Modelling, 2012. **229**(0): p. 25-36.
20. Gerber, D.J. and S.-H. Lin, *Design optioneering: multi-disciplinary design optimization through parameterization, domain integration and automation of a genetic algorithm*, in *Simulation in Architecture and Urban Design*. 2012, ACM.
21. 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, 2014. **38**: p. 59-73.