PROTOTYPING GENERATIVE ARCHITECTURE

Experiments on multi-agent systems, environmental performance and 3d printing

SEVIL YAZICI¹, AND DAVID J. GERBER²

¹ Faculty of Architecture and Design, Ozyegin University, Turkey
sevil.yazici@sevilyazici.com
² School of Architecture, University of Southern California, USA
dgerber@usc.edu

Abstract. Computational design was developed to solve complex problems in architecture and to enable the establishment of systems with complex properties in a holistic manner. With the enhanced capabilities of computational design, there are possibilities to develop integrated approaches to adapt to multi-faceted design problems. Swarm-based multi-agent systems (MAS) are already used as generative bottom-up methods in various design operations, including form-finding and optimization. This study presents a systematic approach, in which multi-agent systems are informed by the environmental performance assessment data where the output is directly linked to the 3D printing process. The intent is to increase efficiency within the design and prototyping process by integrating performance and fabrication into the early stages of the design process. The proposed method has been applied as a case study to a diverse group of students and professionals. The results have proven that applying this systematic approach enabled the designers to achieve highly sophisticated, formal and organizational outputs, with enhanced spatial and geometric qualities.

1. Introduction

Goel defines design process in four phases, including problem definition, conceptual design, design development and detailing (1992). Although there are different definitions of the design process, it is possible to accept that there is a hierarchical order between different phases in conventional design processes. These phases differ based on the type of information they include and their level of detail. They also differ in terms of abstraction, parameterization and kinds of design exploration in each phase. Architecture and engineering professionals need to define objectives, propose and iterate on options, by analysing these options with respect to the existing goals and make uncertain decisions in early design phases (Schön, 1983). As Simon
states, design is by definition an ill-defined problem computationally as there are multiple solutions typically as a result of multiple objectives (1973). So the synthetic endeavour of design is in part a human design decision making process in which the privileging of viable design alternatives is always a goal of the design workflow.

An integral computational model promotes an understanding of material, form and performance not as separate elements, but rather as complexly coupled interrelations (Hensel & Menges, 2008). Solving design problems in the systematic CD methodologies, including form, performance, material and fabrication constraints have been investigated through different perspectives (Menges, 2008; Oxman, 2009). However, there is a necessity to develop a more comprehensive approach to adapt to these multi-faceted problems in the design process, by expanding the formal and organizational capabilities of architects and design teams’ tools, techniques, and methods. Multi-agent systems (MAS) have been used in the design process as generative bottom-up strategies for form finding, optimization and search in the design domains (Gerber, 2014). Our hypothesis asks if it is possible to enhance formal and organizational capabilities of design in concert with performance assessment, MAS and fabrication constraints. This paper presents a systematic approach for form-finding, and where 3D printing is used in the architectural design process, in which MAS are informed by environmental performance data, specifically solar radiation values.

2. Methodology

The methodology of our design experiment was developed as design protocol deployed in a CD workshop setting. The research is develop in an educational setting in which the participants learn the design protocol and present data and results which provide the evidence for our discussion. Different design tools are used in the process, in order to explore their impact and role on design. The design protocol consists of four stages including 1) form-finding, 2) deploying a multi-agent design system, 3) performing environmental performance analysis based on solar radiation, and 4) digital prototyping of the complex geometric results via 3D printing. The workflow, data and model flow are explained for the system and possible iterations are created by the system.

The workshop was planned for a two and a half day time frame and there was no pre-condition for the selection of the workshop participants, which are considered as novice designers and non-expert computational designers. Twenty-seven undergraduate students, graduate students and professionals from various local universities, with diverse backgrounds and differentiated level of knowledge attended to the workshop.
2.1. SYSTEM COMPONENTS

System components can be described according to the design protocol [FIGURE 1]. The workflow is built upon the NURBS modelling design environment Rhino, the visual and parametric scripting environment Grasshopper and physical simulation based via the Kangaroo Grasshopper plugin for the form-finding. Simulation plug-in Ladybug for Grasshopper is implemented for the environmental performance assessment, specifically solar radiation. The necessary weather data for the solar radiation is ascertained via the EnergyPlus software and database. Prior to the simulation, GhPhyton is installed and activated to enable the data transfer from Ladybug and EnergyPlus software. A custom swarm based algorithm developed in the Processing 2.0 environment is implemented for the multi-agent design system. In the final stage, the resulting models associated data sets are brought back to Grasshopper, Rhino and Autodesk Project Miller respectively, to process the model further for the digital prototyping. Two machines are used for the 3D printing, including ProJet 1000 and 3D Touch.

2.2. FORM-FINDING

The graphical interface of the Kangaroo Grasshopper plugin physics engine is used for interactive simulation, optimization and form-finding. The parametric script used in the process is defined as a physical model established by defining strings and weights, based on the hanging chain model of Gaudi. It is used to test the feasibility in terms of design context and constraints established by the designer and to find the static equilibrium of the complex formal geometry of the experiment (Sweeney & Sert, 1960). A stable form is generated based on effective forces, and the geometry is hence optimized i.e. form found. Through the Kangaroo physics engine, springs and unary force is connected to force objects. Following the assignment of the curves drawn by the users, and the designers changing simulation parameters in order to design explore formal configurations, a solution space of design geometries is generated. In parametric design when the design parameters change, the overall design can respond as a holistic system through computation. Thus, various options are generated with great geometric variability and yet topologically similar. Because it was possible to generate this solution space of design variants, a rich formal repertoire is created during the process, affording the designer to make informed choices based on a larger palette of design alternatives. The geometries are then scaled to fit in a 1000 by 1000 unit square, in order to normalize the sizes for compatibility with the Processing based multi agent system (MAS) for design.
2.3. ENVIRONMENTAL PERFORMANCE ASSESSMENT

Our design experimental models are representation of systems with which we assess the system performance based on defined conditions and objective functions. Following the form finding process, an open source environmental performance analysis software Ladybug within Rhino Grasshopper is integrated to undertake solar radiation analysis. Ladybug allows the design team to import and analyse weather data within the Grasshopper visual scripting environment facilitating a connection to the database and simulation engine EnergyPlus for running radiation analysis. The environmental data, '.epw' file, is read by EnergyPlus for ascertaining the radiation values of the design geometry for a specific location, based on data from the US Department of Energy. Climate data for Los Angeles, California is used and then further detailed by specifying time ranges based on hours, days and months in the analysis. Thus the radiation values are calculated for the geographic location specified and the numerical values determined are exported as a text file for use by the our bespoke Multi-Agent Systems scripts in the Processing Integrated Development Environment (IDE).
2.4. MULTI-AGENT SYSTEMS (MAS)

Following the form finding and environmental performance analysis, the output data (the mesh as a tessellated `.obj` and the unit values for each tessellation) is imported into one of our bespoke scripts, `.pde file`, developed on the open source programming language Processing 2.0 environment (Sanchez, 2013). Through these scripts, it is possible to regenerate the geometry through the interaction of the MAS with the mesh i.e. surface. The agents are programmed to make movement and trajectory decisions based on local information including intensity values from the simulation, proximity to neighbours and trails left by other agents. The agents are modelled on the Boid by Craig Reynolds and have stigmergic behaviour in order to approximate connectivity requisite of a tectonic system. The MAS is based on simple flocking behaviours weighted by the data and recursive response to the overall dynamics. Each agent has ability to extract the data from the simulation, paired with its corresponding point on the mesh object. The agent’s environment is a collection of points to which it is constrained, and each point is assigned an intensity score (that of more or less solar radiation) based on the data taken from the simulation (Gerber & Shiordia, 2014). Based on the agent movement, new geometric configurations are generated. By adjusting the parameters, separation, cohesion, alignment, and solar radiation weighting factors, of the agents or how the agents are spawned, new formal organizations are achieved. The workshop participants were able to adjust and design to explore these parameters in order to generate feasible forms in conjunction with assessing the overall formal organization. The numerical data generating geometry were exported as text file and re-generated in 3D geometric modelling medium, Rhino. By running the Processing scripts, it is observed how the model is displayed, and problem areas were identified. The intensity of the agent behaviour parameters is adjusted by increasing or decreasing a set of limited parameter and ranges. This is done to ensure the participants are learning without too much cognitive overload and to focus on the most influential agent parameters and hence behaviours. Our workshop scripts are automatically configured to export a text file every 30 frames. Each text file obtains a list of coordinates for all the agent positions at that particular frame used in final geometrical operations to move from point based positions into 3D models that are solid geometries, for 3D printing.

2.5. 3D PRINTING

Based on developments in digital tools and techniques, it is possible to generate forms with high level of complexity and to translate model input into a building or a building component through digital fabrication
accurately. The widely used term digital fabrication is described as computer aided operations, in which material is formed by subtractive or additive methods. These processes are investigated in two fundamental groups: Computer Numerical Control (CNC) and Rapid Prototyping (RP). In our RP operations, the product is generated by adding layers of material (Seely 2004), through the use of 3D printers. Although in 3D printing geometries of all types of complexity can be produced, there are a series of practical constraints based on the material and machine. Here the workshop is mostly limited by material thickness, bounding box, and time limitations.

Following the MAS application, text files, generated with Processing code, as well as ‘.obj’ files were brought in Grasshopper parametric design environment, to re-generate the geometry, based on the MAS. The intent was to generate the geometry derived from the emergent motion paths of the agents. Each line of the text file represents a set of points in 3D space corresponding to the positions/paths of the agents. When the text file is brought into the Grasshopper, the position of the agents at a given frame is represented by coma-separated values, as simple XYZ coordinates. Through our Grasshopper definition we automatically draw points corresponding to the coordinates in the text files as a set of curves. Finally, the curves are given a parameterized thickness in the script in order to be RP fabricated. The curves are given volume by a piping operation, where the profile is also parameterized within the script. Circle cross-sections were assigned to the curves in these experiments for consistency and cross comparison. By baking the geometry, further adjustment and rendering is performed for final presentation and RP fabrication using Autodesk Project Miller. By this tool the single surfaces were merged into one to be fabricated in 3D printer. Two different printers were used in the process, including ProJet 1000 and 3D Touch. ProJet 1000 are used to fabricate plastic pieces in high resolution with a detailed and smooth surface finishing. One or more geometries can be fabricated simultaneously by arranging the models in the build volume. The speed of fabrication is 12.7 mm per hour in layering vertically. The material used is a white polymer. The speed of the 3D Touch for the fabrication is a maximum of a 15 mm³ per second. Acrylonitrile Butadiene Styrene (ABS) is used as material and could be selected in green or white. The simplified geometry could be fabricated seamlessly in 35 minutes by 3D Touch printer.

3. Results

The participants in the workshop ranged from 1st-year undergraduate students to professionals with different levels of architectural knowledge. It was determined that the CAD experience of participants was based primarily
on conventional representational techniques, including 2D drafting, 3D geometric modelling and visualization. Interpreting new concepts, such as algorithmic design and performance issues, internalizing the knowledge, and transferring the data among six different software programs are significant challenges considering the time limitations of the workshop, which lasted for two and a half days. Although the participants had different interpretations regarding the concepts and terms, the results show that applying this method enables highly complex and differentiated tectonic organizational outputs with enhanced spatial and geometric qualities. While the participants worked with objective data, parameters and computational algorithms, they also used their intuitive knowledge in setting the parameters, resulting in a high degree of variation in the solutions [FIGURE 2-3].

The constraints during the workshop are identified; they were based largely on the digital fabrication, i.e., 3D printers. ProJet 1000 and 3D Touch were used as 3D printers, which were restricted by their table dimensions 171*203*178 mm and 275*275*210 mm respectively. The speed of digital fabrication played a significant role in the process, since the fabrication was limited to two days. One important challenge encountered in the process was the complexity of the geometries generated by MAS and their translation for the 3D printing process.

Figure 2. Output of the studies; Hasan Caner Uretmen, Ege Simsekalp and Ece Alan.

Figure 3. Output of the studies; Melis Baloglu, Omer Kirazoglu and Merve Akdag Oner.
4. Conclusion

As part of the applied method, the computer is used not only as a tool for representation but also as a generative design tool, in which form, performance and fabrication constraints are evaluated in an integrated system. In this approach, the architectural designer becomes an actor who directs the design process with parameters, rules and relationships in the conceptual design phase. Although the method in this paper proposes a comprehensive system, in which form-finding, multi-agent systems for design, environmental performance assessment and digital fabrication are holistically evaluated, it is necessary to develop automation through feedback loops between different steps of the method. For future lines of inquiry in this work, the intent is to incorporate real-time data transfer between the form-finding and the environmental performance assessments, as well as an improved optimization module.

In parallel with the technology, computational design and digital fabrication tools are widely used in the architectural design process. Thus, architects and designers need to be proficient in terms of these skills. For that reason, the issues of re-evaluating architectural design process and re-designing architectural education to include innovative approaches should be widely investigated. An integrative approach is necessary in which form-finding, performance assessment and digital fabrication are evaluated holistically. More studies should be undertaken that reflect upon this issue in the practice and education of architecture. We investigated through the workshop how different groups of people, including novice designers at the beginning of their careers; professional architects and researchers approached the problem in a similar way. All the process was considered unknown and new. Although the novice designers and professional architects approached the problem in a similar way, their outputs were very different. In terms of future research, more studies should be undertaken to investigate complex design problems in the architectural education and profession. Architectural design involves managing multi-faceted problems, which means the field must also address complexly coupled performance criteria.

What we did uniquely is to do the workshop in a very short time frame. We also brought together the physical and the digital in order for students to learn about bottom up design and for them to see how we currently and very easily prototype with these forms. In that regard we previewed a set of potentially influential techniques and workflows that will effect design exploration and by rapid prototyping the palette of locally (bottom up) informed global (top down) design alternatives. While bottom up design models and methods are unwieldy, they have the potential for generating surprising and unexpected results of both aesthetic intricacy and beauty and
of higher performance than can be manually designed, given the real limitations of time, cognitive load, and resource. The workshop itself is a prototype of a new methodology already on the horizon for architects and others to begin to work with and incorporate into their tool kits, and workflows. What our work begins to presents is new ability to design explore formal intricacy and to link this aspect of design to both performance criteria embedded in bottom up local rules of agent models, with those of global outcomes made tangible for human design decision making and subjectivity, via rapid prototyping.

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References
