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A multi-agent approach for performance based architecture: Design exploring geometry, user, and environmental agencies in façades

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ABSTRACT

This paper presents research on the use of multi-agent systems (MAS) in architectural design with the goal of both improving and partially automating the design process as well as the design outcomes in terms of geometry and environmental performance. The work is based upon research on agent based modeling and simulation techniques (ABMS), and the combination of analytical and optimization methods with geometric modeling and user centered design. The motivation is to render more accessible the exploration of the generative aspect of bottom up design techniques when coupled with optimization and performance criteria. The objective of the work is to develop and test a design methodology, which enables designers to explore larger sets of informed solutions by coupling design requirements and generative design techniques with validated simulations (i.e., environmental analysis) based partly on the inclusion of user light preferences early in the design process. The development of the proposed methodology and the implementation of the design system for a building façade are described, while the robustness and validity of the framework is initially tested by applying it to the generation and optimization of façade panel configurations of an office building. The results show that the MAS for design system can generate unique design configurations that perform environmentally (daylight factor analysis) better than a façade with normative façade shading.

1. Introduction

With the increased access to computational design tools and the consequent rapid evolution of algorithmic design methods [49,73], associative parametric modeling [17,39], and multi-disciplinary design optimization [19], design teams have been provided with a new set of design exploration possibilities. As a result, architecture is now experiencing a proliferation of approaches and techniques to generate, rationalize, and optimize design processes and outcomes. In the past decade, simulation has played a more significant role in the design practice for gaining insight and evaluating different performance criteria, including risk, cost, energy efficiency, structural efficiency, lighting, and social utility [7,13,80]. In architectural and urban design discourse, there exists a burgeoning interest in agent based modeling and simulation (ABMS) and in non-linear systems as a means to not only improve the design process but also to improve *design exploration* through adaptation and emergence, facilitating the production of higher performing design outcomes without reducing geometric intricacy. Given these developments, an increasing number of building designs incorporate geometrically complex freeform building envelopes and structures [53]. Modeling of non-Euclidean geometries and exchanges of data between expert disciplines have facilitated the need for advancing active synchronous collaboration, more rapid exploration of design alternatives, and greater management of the complexity of design problems. In some cases the design modeling has been inclusive of environmental settings and information (e.g., daylight factor analysis, heat gain), user centered (e.g., end-user preferences and design feedback) and structural (e.g. stress analysis, force/flow distribution) feedback loops to name a few [18,23,35,39]. Although, there has been a significant interest in the performance based design and the development of integrated workflows for environmental factors [8], there remains a number of critical opportunities to integrate further the ability to *design explore* in an empirically informed fashion where design creativity is enhanced by bottom up exploration methods and engineering based optimizations. In this paper, we point to the lack of contribute to the development of integrated and automated digital workflows during the design process and we introduce a design methodology which; (1) can combine generative design techniques with analytical data and user collected data as optimizing agencies; (2) is extensible; and (3) adaptable to different design variables, design topologies, and types of analysis, such as environmental and/or structural analysis. We utilize multi-agent systems (MAS), where a combination of multiple agent types is used.

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By considering the computer as an active collaborator of the designer, one of our research goals is to enable design teams to quickly generate, measure, and optimize complex geometries across a set of complexly coupled design objectives and in this iteration of the MAS, specifically, environmental performance analyses. The work is also motivated to address a notable gap in architecture's application of emergent systems and generative agent strategies, namely that the majority of the precedent work in the literature is based on a single type of approach, that of the swarm or boid. The work conjectures that through the development of a MAS, design teams can intuitively explore a larger design solution space by integrating analysis tools with user related data in order to inform and improve an automated design process [41,60,65,74]. The research developed presents a generative design system that offers design alternatives that go beyond the geometry-only related objectives but rather and uniquely, are informed by environmental analysis and user preferences i.e., performance criteria and objectives. The research goals are manifold including: (1) a desire to bring to architecture the state of the art in non-linear and emergent design systems; (2) enable the realization of intricate and formally complex designs, measured for their empirical performance across multiple objectives; and (3), to measure the benefits of a MAS approach for aiding design teams to design with complexity and with greater certainty in the performance criteria discussed subsequently. The overall goal is to generate complex and freeform architecture that is equally outperforming manual and deterministically limited solution spaces across multiple performance objectives, highly relevant to contemporary quotidian design practices [38,39,59]. It should be noted the demonstration design use case, a geometrically complex façade, is purposefully idiosyncratic and intricate, however the system is conceived as applicable to more normative geometric systems, nevertheless we use the complex as a purposeful base case for testing the system but also for demonstrating how complex can be found to out perform the simple. The proposed design methodology's outcomes contribute to the improvement of the design process by reducing the design cycle latency through producing more valid design alternatives from which a design decision can be made more rapidly as well as produces more optimal design variants than those produced in a purely manual, deterministic or non generative approach.

Specifically, in this paper, we apply, test and calibrate the proposed MAS design technique, as well as illustrate a design case study for measuring the benefits and limitations of such an approach in an architectural context. In order to provide a better understanding of the MAS design technique introduced in this paper, an experimental case study that integrates end-users lighting preferences with environmental analyses early in the design process of a building envelope with goals to increase daylight availability in the interior space and improve the end-user's comfort is presented. The experimental case study includes the development and implementation of a MAS for the generation of design alternatives of a non-structural building component (i.e., façade panels), which is based on combining environmental simulation and analysis and user preferences constrained by geometric and fabrication logics and limits. The system is run based on collected data from participants in a virtual office space. The results include a set of geometrically intricate design alternatives, which account for both improved energy efficiency and user preference targets.

The paper is structured through six sections. In Section 2 we present a literature survey on the use of MAS in Architecture Engineering and Construction (AEC) and related domains, and our agent definitions. In Section 3 the design problem, research objectives, methodology and the implementation of our system for a specific experimental design case are described. In Section 4 the results and analysis of the experimental design are presented. In Section 5 limitations of the research to date and future work are outlined. Lastly, in Section 6 a summary of contributions and conclusions of the research are discussed.

2. Agent based modeling and multi-agent systems

Research has shown that the complexity and uncertainty, encountered in design problems, can be more effectively addressed with distributed computation and artificial intelligence [27,43,79]. However, given the nature of design problems as *'ill structured'*, designers must engage in defining abstractions in order to design explore and optimize computationally [56,64]. The capacity of distributed systems, in this case of a MAS, to abstractly model requirements as agent goals and to adapt to local conditions, has rendered them appropriate for solving a large class of real world problems in a number of domains, including software engineering, financial markets, security and game theory [71,75,78] to name a few. MAS are also related to Complex Adaptive Systems (CAS), which are characterized by their ability to self-organize and dynamically reorganize their components in different ways and across multiple scales [31]. This process allows the agents to negotiate, survive, and adapt within their environments [43], and incorporates evolutionary and generative mechanisms found in nature and the development of mathematical models that simulate physical processes [10]. There exist a number of properties, such as aggregation, nonlinearity, flows, diversity, and mechanisms, such as planning and tagging of internal models as building blocks that are common to MAS and serve as a reference for designing and developing agent-based models that can be synthesized to form a MAS [28,43,70,75]. Due to their modularity, MAS are considered applicable for producing portable, extensible, and transferable algorithms, with better integrated development environments and more applications [43,69].

It should be noted that application of MAS in the AEC industry has been less pervasive. Beetz classifies MAS in AEC under three domains of design generation, namely: knowledge capturing and pattern recognition; simulation and performance of building designs; and collaborative environments [9]. In the fields of engineering and construction, researchers have been exploring the applicability of MAS from different perspectives, such as for collaborative design, construction scheduling and structural optimization to name a few [5,9,30,41]. Agent based simulations have been used in digital fabrication and building construction for their capability to abstract, adapt and simplify real time complexities into simple basic rules [58]. Additionally, there has been impactful research in developing MAS for autonomous collective construction both at the level of algorithms but also at the level of hardware [76,77]. In the field of architecture and computational design, the focus of research so far has been mostly on design generation (form and aesthetic) and simulations [22,61]. Approaches to design generation can be classified as linear and non-linear based on algorithms that operate, either in top-down or bottom up fashions [21,24,63]. Many have argued that top down approaches offer control though not enough design flexibility as they operate on fixed design topologies that are sequentially decomposed [67]. On the other hand, bottom up algorithms can be challenging to apply for design purposes and often exhibit a lack of control in the design outcome [68]. We have found in the literature, a majority of the research in bottom up design approach for architecture has focused on the generative aspects, which have predominantly implemented swarm or boid algorithms [6,12,15,29,41,44]. Snooks argues "Swarm intelligence" enables the encoding of design requirements either into agent behaviors of different populations that belong to interrelated sub systems or within a population with adjustable or differentiated behaviors of one system [41,42]. The distributed nature of agent based models enables the mutual negotiation of relationships between different design parameters, such as program and form or structure and ornament [65]. Whereas, Menges uses swarm-based agent models in order to establish communication, across different design environments (architectural design, structural design) and for different hierarchical levels (global geometry, material structure) and thus allowing for the uninterrupted flow of information from input parameters into multiple design constraints [47,51]. However, according to Anumba et al., the encoding of the design requirements (i.e. building