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Computational-based Generative Design Exploration, Multi-Agent System as an Approach

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1 ABSTRACT

Architecture design problems are known for their sequential steps that address a series of several interweaving, competing and/or aligning requirements. Describing them as open-ended, uncertain, solution searching processes makes them complex and ill-structured design problems. One of the methods to deal with nonlinear complex systems is that their components' properties and features must not be pre-determined and studied linearly in isolation. Instead, it is essential to consider the system as a whole, even if it means considering it generally and roughly, and then allow possible simplifications to occur from the dynamic interactions between components. Computational design methods that encounter distributed computation and artificial intelligence, such as Multi Agent System (MAS), showed promising abilities in addressing complexity and uncertainty faced with architecture design problems, as well as they proved positive effect on expanding architecture design exploration (ADE). This study has an interest in MAS capabilities in creating aesthetically innovative and performable architecture solutions.

Therefore, this research intends to investigate the use of MAS in Architecture in the years between 2010 to 2020. It contributes with a detailed examination of research papers to orient future research in the field of MAS. Hence, the applied literature review raises the question of what the proved capacities of MAS are and how future research can challenge it further to widen and develop the use of MAS in ADE and their possible capabilities when addressing building performances such as structural, functional, and environmental. The databases used for selecting these papers are Scopus, Web of Science, SAGE, Science Direct, Google Scholar, Connected Papers, CUMINCAD, IEEXplore, and ACM Digital Library. These studies are organized, analyzed, and compared to pinpoint key innovations in MAS's variable usage, study its applied methods, interesting results, important sources of data, implementation strategies, and shed the light on the gaps and shortcomings to draw a perspective of MAS in architecture. The examined studies are arranged chronographically. Then, each paper is analyzed and classified according to the aim of the methodology, domain, level, scale of application (experimentation level), model generation and optimization methods. Afterwards, a critical review is proposed.

Keywords: Computational Architecture, Design Optimization , Generative, Algorithmic & Evolutionary design, Agent based Modeling and Simulation, Multi-Agent Systems

2 INTRODUCTION

Architecture design problems are known for their sequential steps that address a series of several interweaving, competing and/or aligning objectives without a well-defined or specific design output (Terzidis, 2006). In all cases these objectives not only might align or conflict with one another, they are changed and uniquely defined in every single design problem based on the problem itself, the goal of the design, building program, constraints, client's requirements, surrounding context, etc. In addition, they are open-ended, uncertain, solution searching mechanism with no clear formulation of all required information and aspects any problem-solving processes would need. Therefore, they are identified as complex, wicked, and ill-structured problems (Rittel & Webber, 1973). To elaborate further; there are several clear aspects that complexifies such problems. For instance, the lack of the required definite and clear information for every attribute related to the problem, which challenges more the problem's tackling processes (Suh, 2005). Another aspect is related to creating innovative outcomes, which makes the expected product not specified and cannot be predicted. Another pivotal aspect that complexifies the architecture design problem further, is the nonlinear interrelationship, correlation and causation between whole system's pattern, properties, attributes and behvior observed on the global level and their inter-consequences and interactions of the constituent elements on the local level (Bar-Yam, 2002). It is a phenomenon described as micro-macro effect (Wolf & Holvoet, 2005).

One of the methods to deal with such nonlinear complex systems is that their components' properties and features must not be pre-determined and studied linearly in isolation. Instead, it is essential to take into account the system as a whole, even if it means considering it generally and roughly, and then allow possible simplifications to occur from the dynamic interactions between components (Pantazis & Gerber, 2019). Computational design methods that encounter distributed computation and artificial intelligence, such as Agent based modeling and simulation (ABMS) and Multi Agent System (MAS), showed promising abilities in addressing complexity and uncertainty faced with architecture design problems (Macal & North, 2009), (Erdine & Kallegias, 2016a), (Gerber, Pantazis, & Wang, 2017), as well as they proved positive effect on expanding architecture design exploration (ADE) (Robertson & Radcliffe, 2009), (Liu, Li, Pan, & Li, 2011), (Zboinska , 2015), (Chang, Chien, Lin, Chen, & Hsieh, 2016), (Daemei & Safari, 2018), (Zboinska, 2019). Through the modeling of complex system in the level of their individual constituent, the whole system's pattern, structure and behvior can emerge without being explicitly programmed into the model (Heath & Hill, 2010), (Macal & North, 2010). Therefore, this research has an interest in the applications of MAS in architecture. It aims at developing a collective understanding of MAS capabilities between 2010 to 2020 and suggests future research.

3 MULTI AGENT SYSTEM DEFINITION AND NOTIONS

A Multi-Agent System is a computerized system composed of multiple interacting collaborating agents within an environment. These agents act autonomously and collaboratively to achieve more complex goals that any of the agents can do by itself (Pantazis & Gerber, 2018). Most research suggested that in order to deal with complexity and uncertainty faced in architectural design problems, non-conventional design methodology must be addressed. It is effectively proven that distributed computation and artificial intelligence can overcome such difficulties (Beetz, Leeuwen, & Vries, 2004) (Jennings & Wooldridge, 1999). Not only, but also the given nature of the design problem as "ill-structured" raises the necessity and ensure the provision of computational abstractions for design exploration and solutions optimization (Gerber, Pantazis, & Wang, 2017). The applicability of a distributed system provided by MAS described in abstractly fashioned agents with defined goals adapting to a local conditions, made MAS an appropriate for solving a large class of real world design problems, in several domains such as the work of (Davide , Pilosof, Hadas , Yahav, & Kalay, 2019) (Erdine & Kallegias, 2016a) (Davide, et al., 2016) and (Fernandes, 2013) (Viehweider & Chakraborty, 2015) to name a few.

4 LITERATURE REVIEW APPLIED METHODOLOGY

4.1 MAS in AEC Field, Collection and Selection

There is a significant interest in the field of MAS seen in the work of experimentalists in architecture in recent years. These include researchers, units, and practitioners such as David Jason Gerber, Achim Menges, as well as practices such as Zaha Hadid Architects and Morphosis Architects. Such approaches utilization is considered a paradigm shift in architecture thinking and exploration for more efficient solutions, challenging the complexity of a design problem. This section presents a brief representative of MAS in AEC, in the years between 2010-2020. The databases used for selecting these papers are Scopus, Web of Science, SAGE, Science Direct, Google Scholar, Connected Papers, CUMINCAD, IEEXplore, and ACM Digital Library. These studies are organized, discussed and compared to pinpoint key innovations in MAS's variable usage, study its applied methods, interesting results, important sources of data, and shed the light on the gaps and shortcomings to draw a perspective of MAS in AEC. Literature retrieval method is undertaken as follows: (Determine the time frame; (2010 – 2020) / Determined keywords: Agent based/ agent-based modeling (ABM)/ Agent based simulation (ABS)/ Agent based modeling and simulation (ABMS Multi agent system) / The targeted Language: English/ Search in Scientific Database Platforms: Scopus, Web of Science, SAGE, Science Direct, Google Scholar, Connected Papers./ Downsize them into papers concerned with architecture design phase./ Select a sample to show-case and represent MAS as a paradigmatic effect in the design process.)

4.2 Literature Review Analysis and Interpretation

The undertaken study went through several steps. First, they are arranged chronographically. Then, each paper is analyzed, classified and discussed according to aim of the methodology, domain, level, scale (application), model generation logic, optimization methods, refer to Figure 1, Table 1 and Section 6.

5 ANALYTICAL STUDY AND DISCUSSION OF MAS APPLICATION IN AEC

MAS is not just a system. MAS is a concept that can be seen in different areas and implemented on different scales to solve varies problems. There are several contributions made to the applicability of MAS in AEC they can be classified into three domains: knowledge capturing and recognition in drawings and sketches, simulation and performance of building designs, and collaborative environments (Beetz, Leeuwen, & Vries, 2004). The research will concentrate on the simulation and performance domain.

Levels of Design Problem Complexity: The usage of MAS can be seen in several precedents from conceptual design phase, seen in the work of (Erdine, 2016b) (Gerber, Pantazis, & Wang, 2017) (Guon & Li, 2017) (Yi & Kim, 2015) to name a few, to fabrication, found in the work of (Baharlou & Menges, 2013) (Gerber & Pantazis, 2016a) (Pantazis & Gerber, 2016) (Yazici & Gerber, 2016), (Smith, Danahy, & La Rotta, 2020). These contributions can be categorized into five different levels of process complexity. The first level is aesthetic-driven optimization. It was found that aesthetic is not usually a target or a measured target however it comes in form of interesting or exciting and novel outcomes and its suitability is measured in accordance to a targeted single performance or targeted multiple performances and/or fabrication feasibility, such the work of (Pantazis & Gerber, 2014) and (Smith, Danahy, & La Rotta, 2020). The second level is single-discipline optimization for instance; environmental performance (Sugihara, 2014), (López & Gerber, 2014), (Yi & Kim, 2015), (Pantazis, Gerber, & Wang, 2016), (Gerber, Pantazi, & Wang, 2017), (Pantazis & Gerber, 2018), (Agirbas, 2019), Material performance (Tsiliakos, 2012), Functional performance (Davide, et al., 2016), (Guon & Li, 2017), (Ghaffarian, Fallah, & Jacob, 2018), (Davide , Pilosof, Hadas , Yahav, & Kalay, 2019), (Fuchs & Neumayr, 2020). The third level is multi-discipline optimization, where more than one performance is targeted – such as. Environmental and Structural Performance, (Gerber, Shiordia, Veetil, & Mahesh, 2014), (Gerber, Pantazis, & Marcolino, 2015), (Pantazis & Gerber, 2016), (Gerber, Pantazi, & Wang, 2017), (Pantazis, 2019). Environmental Performance and rationalization such as (Baharlou & Menges, 2013), (Gerber & Pantazis, 2016b). Aesthetic and structural performance and rationalization, seen in the work of (Smith, Danahy, & La Rotta, 2020) And the Fourth level is multi-discipline optimization and digital fabrication such as (Pantazis & Gerber, 2014), (Schwinn, Krieg, & Menges, 2014), (Gerber D. J., Pantazis, Marcolino, & Heydarian, 2015), (Erdine, 2016b), (Gerber & Pantazis, 2016a), (Yazici & Gerber, 2016), and as previously mentioned Building Systems (Wang, Yang, & Wang, 2010), (Lee, 2010), (Joumaa, Ploix, Abras, & Oliveira, 2011), (Ramchurn, Vytelingum, Rogers, & Jennings, 2011), (Klein, et al., 2012), (Zhao & Suryanarayanan, 2011).

Design Applications Scales: Multi-Agent systems have been applied to design problems of varying scales ranging from Urban design (López & Gerber, 2014). As well as building envelope design, (Sugihara, 2014), (Gerber, Shiordia, Veetil, & Mahesh, 2014), (Yi & Kim, 2015), (Gerber D. J., Pantazis, Marcolino, & Heydarian, 2015), (Gerber D. J., Pantazis, Marcolino, & Heydarian, 2015), (Pantazis, Gerber, & Wang, 2016), (Pantazis & Gerber, 2018) (Agirbas, 2019) (Gerber, Pantazis, & Wang, 2017). In addition, structural element design like shading system or pavilion or a column, seen in the work of (Tsiliakos, 2012), (Baharlou & Menges, 2013), (Pantazis & Gerber, 2014), (Gerber, Shiordia, Veetil, & Mahesh, 2014), (Schwinn, Krieg, & Menges, 2014), (Gerber, Pantazis, & Marcolino, 2015), (Pantazis & Gerber, 2016), (Erdine & Kallegias, 2016a), (Gerber & Pantazis, 2016a), (Yazici & Gerber, 2016), (Gerber, Pantazi, & Wang, 2017), (Pantazis, 2019), (Smith, Danahy, & La Rotta, 2020). Layout configuration driven by users' behavior simulation (Lee, 2010), (Klein, et al., 2012), (Davide, et al., 2016), (Guon & Li, 2017), (Ghaffarian, Fallah, & Jacob, 2018), (Davide , Pilosof, Hadas , Yahav, & Kalay, 2019) (Fuchs & Neumayr, 2020). Energy management demand such as (Wang, Yang, & Wang, 2010), (Lee, 2010), (Joumaa, Ploix, Abras, & Oliveira, 2011), (Ramchurn, Vytelingum, Rogers, & Jennings, 2011), (Klein, et al., 2012), and (Zhao & Suryanarayanan, 2011), to product design (Madhusudan, 2005) , (Sugihara, 2014).

MAS in terms of the Architecture Design Process: In order to comprehend more the strategy and technique of using MAS, it can be seen in terms of a design cycle stages. Any design cycle consists of synthesis (modeling, generation), analysis (simulation) and evaluation (examining and searching method for an optimal solution; optimization). In MAS, all these stages are represented as agencies, combined, and work autonomously and collaboratively to reach specific design goals assigned by the design team. MAS can be used in generation level (modeling) in terms of singular agency like the work of (Yi & Kim, 2015) (Guon & Li, 2017), and simulation (in simulating user behavior), seen in the research of (Dijkstra, Timmermans, & Jessurun, 2000), (Klein, et al., 2012), (Davide, et al., 2016), and (Davide , Pilosof, Hadas , Yahav, & Kalay,

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2019), for evaluation and or optimization process (Madhusudan, 2005), (Tsiliakos, 2012), (Sugihara, 2014), (Pantazis & Gerber, 2014), (López & Gerber, 2014), (Schwinn, Krieg, & Menges, 2014), (Pantazis & Gerber, 2016), (Pantazis, Gerber, & Wang, 2016), (Erdine & Kallegias, 2016a), (Gerber & Pantazis, 2016a), and (Yazici & Gerber, 2016). Or Undertaken throughout the whole process, collaborating between agencies from generation to evaluation and optimization, where behavioral design methodologies do not only negotiate for geometry generation but also geometry generation in regard to local and global performance objectives that might align or compete with one another until reaching to the most optimal one (Wang, Yang, & Wang, 2010), (Joumaa, Ploix, Abras, & Oliveira, 2011), (Klein, et al., 2012), (Gerber, Shiordia, Veetil, & Mahesh, 2014), (Yi & Kim, 2015), (Gerber, Pantazis, & Wang, 2017), (Gerber, Pantazi, & Wang, 2017), (Pantazis & Gerber, 2018), (Agirbas, 2019) and (Pantazis, 2019).

In synthesis (generation) stage, MAS has the ability to standalone through describing an agent-based modeling logic like the work of (Baharlou & Menges, 2013), (Sugihara, 2014) (Pantazis & Gerber, 2014), (Schwinn, Krieg, & Menges, 2014), (Pantazis & Gerber, 2016), (Davide, et al., 2016) (Pantazis, Gerber, & Wang, 2016), (Erdine & Kallegias, 2016a), (Gerber & Pantazis, 2016a), (Gerber & Pantazis, 2016b), (Yazici & Gerber, 2016), (Gerber, Pantazi, & Wang, 2017), (Guon & Li, 2017), and (Pantazis, 2019). OR it can be integrated with or governed by a generative approach (ex; Swarm Intelligence (SI), L-System (LS), Cellular Automata (CA), etc.) in several forms. To exemplify; all of (Tsiliakos, 2012) (Gerber, Shiordia, Veetil, & Mahesh, 2014), (Agirbas, 2019) used the logic of SI in generation stage, while (López & Gerber, 2014) (Yi & Kim, 2015) (Gerber, Pantazis, & Marcolino, 2015) (Gerber D. J., Pantazis, Marcolino, & Heydarian, 2015) (Gerber, Pantazis, & Wang, 2017) (Pantazis & Gerber, 2018) used LS. In addition, (Dijkstra, Timmermans, & Jessurun, 2000) who used CA.

The efforts of optimization are enormous and can be enumerated in two areas; MAS can integrate an agent-based searching method (hypothetically speaking a linear form) or integrate heuristic searching method. Researchers who adopt MAS with an agent-based searching model always build a framework to reach to a better solution better than the base case, or embrace a concept, where reaching for a better solution is stimulated to find a better one than the previous one (a linear and in some cases exponential form), or tackling the area where when the searching method stops the resulted solutions are likely to be nearer to sub-optimal one than when the searching process started seen in the work of (Madhusudan, 2005), (Lee, 2010), (Ramchurn, Vytelingum, Rogers, & Jennings, 2011), (Tsiliakos, 2012), (Baharlou & Menges, 2013), (Sugihara, 2014), (Pantazis & Gerber, 2014), (López & Gerber, 2014), (Erdine, 2016b), (Erdine & Kallegias, 2016a), (Pantazis & Gerber, 2016), (Pantazis, Gerber, & Wang, 2016), (Gerber & Pantazis, 2016a), (Yazici & Gerber, 2016), (Ghaffarian, Fallah, & Jacob, 2018), and (Gerber & Pantazis, 2016b). In the area of optimization MAS uses as a rule-based searching methods written in agent's logic of thinking, where they use a linear searching system which always take a longer time than when using any other heuristic searching method.

MAS and Heuristic Searching Methods: In the area of integrating a heuristic searching method, the efforts are significant. To exemplify; (Klein, et al., 2012) used Markov Description Problems method, (Gerber, Shiordia, Veetil, & Mahesh, 2014)and (Gerber, Pantazi, & Wang, 2017) used Multi-objective optimization, (Yi & Kim, 2015) used Genetic algorithm, (Guon & Li, 2017) used Evolutionary Approach, (Wang, Yang, & Wang, 2010) used practical swarm intelligence, and (Gerber, Pantazis, & Wang, 2017), (Pantazis & Gerber, 2018), and (Pantazis, 2019) used hill climbing and simulated annealing. Despite these massive efforts in utilizing a heuristic approach, researchers did not clearly state how, or why they are using these approaches specifically. A more detailed explanation for the selection and how these heuristic approaches are integrated is strongly needed to be provided, which challenges and inspire the further research in this area. Solving multi objectives problems has been a challenge to researchers for a very long time until the first use of the evolutionary algorithms (EAs). It motivates them by its population-based nature of evolutionary algorithms - to solve such multi-objective problems (Coello, Lamont, & Van Veldhuizen, 2007). Evolutionary driven design targets the search for the optimum solution(s). It is applied after the initial level of conceptual design as a search engine, where applying evolutionary design supports the search of broader ranges of alternatives (Gerber & Lin, 2013).

Genetic Algorithm is one of the mostly used and successful investigative search methods for optimum solutions proved by several papers such as (Torres & Sakamoto, 2007) (El-Sheikh & Gerber, 2011) (Varendorff & Hansen, 2012) (El Daly, 2014) (Elghazi, Wagdy, Mohamed, & Hassan, 2014) and (El-

Maghraby, 2016). Despite its promising capabilities limited number of papers utilized it in its search process for an optimal solution such as the work of (Yi & Kim, 2015). In this paper the researchers used a simplified design problem, where they used MAS in the modeling logic and did not appear further in the rest of the design process. Another attempt by (Smith, Danahy, & La Rotta, 2020) , where the researcher created three combined methods in one process. Each method tackle a part of the design process; topoform creates the column geometry using evolutionary-multi agent software, capable of generating diverse topological designs with structural and geometric performance governed and selected by GA integration - matform an agent based additive manufacturing tool-path able to produce gravitational material affects while adapting to local structural and geometrical data- and finally a matSim, a material physics simulation environment to simulate additive manufacturing material structurally and aesthetically in a high resolution. The proposed method showed a successful integration between GA with MAS, which inspire and challenge the research further in this area.

Human behvior in MAS: Research has proven that designing according to user needs, behavior and preferences has a great potential to reduce energy consumption. A usual applicability of user-related information is by informing the design process of user's possible interactions, comfort levels, preferences, and occupation schedules. In addition, research has proven that user-centered design could significantly increase the efficiency of any tested system. Despite these promising potentials and efforts applying them is usually harder as the designer does not necessarily have accurate information of possible occupants' behavior. In other words, people do not necessarily function according to these assumptions of occupancy pattern or such fixed schedules. Therefore, in the area of energy demand, (Klein, et al., 2012) presents, implements and integrates MAS encompassing Markov decision problems (MDPs) to model alternative management and control of building systems and occupants. Such strategies have a great potential in reducing energy through direct cooperation and coordination with building occupants in addition to improving control of building systems and energy resources. However, in the area of integrating MAS and ABMS researchers' attention were taken more towards behavior of human being, believing that instead of designing and constructing and then do post-occupancy assessment, they now design the other way around (bottom-up method). Through using anticipated behavior of people inside the space and accordingly the building will be created to most satisfy or provide these users with their needs and level of comfort inside the building, in terms of environmental, structural, or functional performance. A common approach of incorporating human-center design is by including user's behavioral model to simulate users' movements, interactions, and responses to examine a proposed design (Dijkstra, Timmermans, & Jessurun, 2000), (Davide, et al., 2016), (Davide , Pilosof, Hadas , Yahav, & Kalay, 2019) or to create a design like the work of (Ghaffarian, Fallah, & Jacob, 2018) in creating a spatial arrangement informed by the users' movements.

Another interesting attempt seen in the work of (Pantazis, Gerber, & Wang, 2016), when incorporating Immersive Virtual Environments (IVE) in the design process. Research has proven that participants perform similarly within IVE as they do in physical environments, and they also feel similar feelings of presence within such environments. To clarify the significance of such efforts, it is important first to define the word performance. Performance is a widely used word with different perceptions in architecture. Grobman and Neuman describe two different levels of performance (Grobman & Neuman, 2012). The first is a broad definition, which includes three dimensions: empirical, cognitive, and perceptual. The other level is the narrow definition, which is concerned with the empirical dimension disregarding the other two dimensions. The Empirical dimension can be translated into computer language; therefore, it is widely used. While the cognitive and perceptual ones mainly rely on questionnaires and statistical measurements, making them hard to achieve. In the work of (Pantazis, Gerber, & Wang, 2016) , they incorporate the use of IVE. This combination is very interesting where they could apply the broader definition of Performance by integrating IVE instance evaluation of a user. By doing this they can integrate designer's intuition into the design process to find an optimal solution technically, cognitively, and perceptually while considering user's experience with the proposed design.

Another research by Fuchs and Neumayr (2020) aims at developing a cross-disciplinary system that capable of generating spatial environments with higher social interactions. The intension is to design an office break out room governed by the occupants anticipated behvior and ensure increased human interaction. The researcher applies two layers of interactions; interactions between office spaces users which are governed by status, affiliation, position etc. and another between the users and the furniture elements such as tables, reception desk, coffee machine etc. Despite this approach is valuable, it still has its limitations, here human behvior and interactions are still hard to be precisely mapped, which always comes at the expense of the whole system accuracy.

The Architecture Problem complication and using MAS: MAS made the integration of structural and environmental performance analysis to be possible, through decomposed design process into multiple agencies that work autonomously and collaboratively. This integration is seen in the work of (Pantazis & Gerber, 2014), (Gerber, Shiordia, Veetil, & Mahesh, 2014), (Gerber, Pantazis, & Marcolino, 2015), (Gerber & Pantazis, 2016a), (Yazici & Gerber, 2016), (Gerber, Pantazi, & Wang, 2017), and (Pantazis, 2019). As well as the integration of material constrains and fabrication requirements in the early design stages, seen in the work of (Baharlou & Menges, 2013), (Pantazis & Gerber, 2014) (Gerber, Shiordia, Veetil, & Mahesh, 2014), (Schwinn, Krieg, & Menges, 2014), (Gerber, Pantazis, & Marcolino, 2015), (Erdine & Kallegias, 2016a), (Gerber, Pantazis, & Wang, 2017), and (Gerber, Pantazi, & Wang, 2017). Despite these essential studies paves the way to creating a system that is concerned with two different performable disciplines, an obvious gap seen in creating a MAS system that integrates environmental and functional performances all together, which challenges the research further to dig deeper in this area.

Spatial Planning, equivalent to word layout in this research; multiple researchers worked in this area from an evolutionary platform, refer to a review by (Calixto & Celani, 2015) concerning this issue. However, in the field of MAS spatial planning has been applied through three different methods: a proposed plan and testing its functional performance according to behavior of users and then adjust it accordingly, seen in the work of (Dijkstra, Timmermans, & Jessurun, 2000), (Davide, et al., 2016), and (Davide , Pilosof, Hadas , Yahav, & Kalay, 2019). A Users' behavioral model is used to create voids (circulation areas) and leftovers are defined as shape solid (functional spaces) like the work of (Ghaffarian, Fallah, & Jacob, 2018). Or MAS is used in achieving spatial relationship and functional requirements in two and three-dimensional, seen the work of (Guon & Li, 2017).

Tools of MAS: Concerning the tools to develop a MAS framework, most researchers develop their own tool or toolkit. In the work of (Sugihara, 2014), the researcher developed an open-source library on Processing called iGeo to help computational designers to explore design possibilities in agent-based algorithms. What is so distinctive about this paper is the detailed description of the code and its technical aspects. Therefore, it is considered a valuable source of inspiration in the realm. Though, other researchers use visual scripting platforms like grasshopper and then apply collaboration by wider platform that requires coding; external software that is concerned with the collaboration between different agents seen in the work of (Pantazis & Gerber, 2016) and (Gerber, Pantazis, & Wang, 2017). With their reliability on iGeo library, they provide detailed technical description, which is also considered valuable source for this research. In the area of human as agents the usage of Netlogo and unity is preferred, seen in the work of (Fuchs & Neumayr, 2020). It has been noticed that utilizing MAS and ABMS requires the designers to create their own design toolkit to apply it, challenging the architects further to master several coding languages such as scripting coding, C# and Java script etc.

6 CONCLUSION AND FURTHER RESEARCH

There are various strategies in applying MAS. It can be used in any design stage, it can appears standing alone in the generation stage in terms of singular or multiple agent-based modeling, or simulation stage or optimization stage, or its agents can be distributed along the process where each agent act autonomously achieving its own local targets while collaborating with the other agents in the same stage or with other agents from a different stage to achieve the global targets, aiming for design exploration and/or optimization. It is obvious from the matrix seen in, Figure 1 , the selected sample fall in the area where agent-based is highly used in generation and/ or optimization level aiming to solve single/multi design problems that reflects system capabilities in addressing different level of design complexity. On the contrary, in the area of aesthetics the efforts are limited which raises the question towards the importance of aesthetics and how can they be measured and achieved so it can be tackled further by the use of MAS and ABMS. Finally using it in the building system and energy demand is noticeable specifically in the prime usability of the ABMS and MAS.

Architects are now capable of dealing with complex design issues targeting several performances at the same time, where MAS is capable of integrating several agents fall under different design stages and loaded with its own set of behaviors and targets. Therefore, their vast capabilities are well-witnessed. To name a few: MAS ability in emergence which results in unexpected designs. Huge solutions spaces resulted when autonomous agents interact with one another while exploring design solutions. They can deal with huge and complex data set, computation and reasoning processes as they are conveniently distributed and modularized by using agents as the main module units. Different agents with varies roles for different practice aspects acting naturally. Dealing with different level of complexity, varies stages of design, different level of complexity and languages, different tasks (generating/ evaluating/ criticizing/ optimizing/ analyzing)., different parts of computational system.

It is also noticeable that agents can come in a form of mimicking human behavior, others acting like a building element and/or becoming as defined manipulators that when connected together they can form a building skin or column or a shading system. It can promote the achievement of several scenarios in the space; multiple users, multiple functions, using multiple sensors to control automation system etc.

In addition, integration of Environmental and structural design problems can be solved in holistic fashion. In addition to merging fabrication constraints while designing and using fabrication constraints as designing drivers. This also reflected that MAS usage seems to have a global-related concern, which is climate change issue, where researcher's intent to design in regard to environmental performance and/or when the process integrates rationalization techniques to ensure material suitability and constructability and reduce expected waste in material. Going for complex design outcomes aesthetically with performable solutions proved the system vast capabilities in handling several design issues without simplifying the design outcome and taking it to a more holistic approach in terms of fabrication rendered the complex forms feasible for construction. However, the selected building types and design problems are still simplified, where most of papers tackle from two to three design objectives at maximum, which still does not reflect a highly complex design issue like designing for a huge shopping mall, hospitals etc., where the objectives with equal importance increase dramatically.

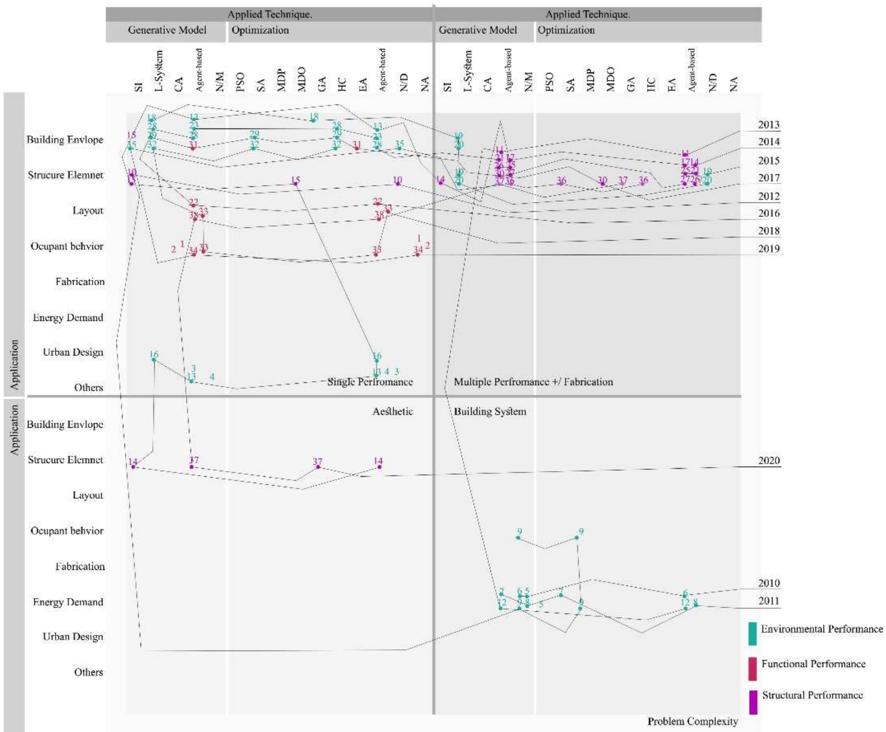

Figure 1: A Matrix Briefing the Applied Study (by author).

In the area of integrating heuristic searching method, relying only on agent-based searching method to find the optimal solution running to what this research called a linear searching process require extensive computation and time as handling that amount of rule-based parameter is endless. Therefore, incorporating a heuristic searching method is more promising to find the local-optimal or near optimal solutions in a reasonable time. Some insights on the optimization processes; Integrating two or more design objectives would complexify the design problem further making it a multi-objective optimization process. This was tackled differently by different researchers; Some would use multi objectives heuristic searching methods.

Others would combine all objectives in one formula where each objective is weighted differently in accordance with the researcher's criteria. And the process is turned into single objective optimization, where the system is trying to minimize or maximize the outcome. This formula would help to find the global optimal solution. However, this optimal solution is defined in terms of the designer/ creator weights to the formula's parameters which consequently affects the result greatly. This means the output is not necessarily the most optimal as for another weight factors the global optimal solution will result in a different one.

On the contrary, optimization based on pareto frontier in multi-objective optimization considered a more valuable technique, as it is seen to the user the different alternatives and where they fall on the pareto graph, how each solution out wins the other in each objective. This results in many alternatives and the designer can afterwards choose intuitionally and according to his/her own design targets which is the suitable or preferred solution. It can also give insights about the different objectives interrelation and correlation inside the system. Finally, the selected heuristic searching method is crucial in affecting the results outcome. They are another rule-based system with their own changing parameters added to the system, like the percentage of crossover to mutation in genetic algorithm. Therefore, defining the most suitable heuristic searching method is another research question. What is the most suitable searching method suitable for the problem at hand, especially with an ill-defined design problem like architecture design problems. Can one heuristic searching method outperform another? What are the internal parameters of the heuristic searching method and how they can drastically change the output? As they would. Should the designer use more than one to ensure the optimality of the output. Many questions can guide the research further in the area of integrating MAS with heuristic searching methods.

	Year	REF	Domain			Complexity					Application								Applied Technique.														
						Aesthetic	single Performance	Perfromance (+	Perfromance +	Building System									Generative Model					Optimization									
			1	2	3	A	B	C	D	E	ENVELOPE	STRUCTURE ELEMENT	LAYOUT	OCT- BHR	FABRICATION	ENERGY	URABN DESIGN	OTHERS	SI	L	CA	Agent-based	N/A	PSO	SA	MDP	MDO	GA	HC	EA	Agent-based	N/D	N/A
1	2000	(Dijkstra, Timmermans, & Jess		●			●							●							●												●
2	2001	(Dijkstra, Jessurun, & Timmermans, 2000)		●			●							●							●												●
3	2002	(Achten & Jessurun, 2002)	●															●				●											●
4	2004	(Madhusudan, 2005)			●													●					●								●		
5	2010	(Wang, Yang, & Wang, 2010)		●						●						●							●	●									
6	2010	(Lee, 2010)		●						●			●			●							●								●		
7	2011	(Joumaa, Ploix, Abras, &		●						●						●							●		●								
8	2011	(Ramchurn, Vytelingum,		●						●						●							●								●		
9	2012	(Klein, et al., 2012)		●						●				●		●							●			●							
10	2012	(Tsiliakos, 2012)		●			●					●							●													●	
11	2013	(Baharlou & Menges, 2013)		●				●				●										●									●		
12	2013	(Zhao & Suryanarayanan,		●						●						●						●									●		
13	2014	(Sugihara, 2014)		●			●				●							Se ve				●									●		
14	2014	(Pantazis & Gerber, Material		●		●			●			●			●				●												●		
15	2014	(Gerber, Shiordia, Veetil, & Mahesh, 2014)		●				●			●	●															●						
16	2014	(López & Gerber, 2014)		●			●										L an			●											●		
17	2014	(Schwinn, Krieg, & Menges,		●					●			●										●									●		
18	2015	(Yi & Kim, 2015)		●			●				●									●								●					
19	2015	(Gerber, Pantazis, &		●					●		●	●			●					●												●	
20	2015	(Gerber D. J., Pantazis,		●				●			●	●								●												●	
21	2016	(Pantazis & Gerber,		●				●				●										●									●		
22	2016	(Davide, et al., 2016)		●			●						●									●									●		
23	2016	(Pantazis, Gerber, & Wang, A		●			●				●											●									●		
25	2016	(Erdine & Kallegias2,		●					●			●			●							●									●		
26	2016	(Gerber & Pantazis, 2016)		●					●			●			●							●									●		
27	2016	(YAZICI & GERBER, 2016)		●					●			●			●							●									●		
28	2016	(Gerber & Pantazis, A Multi-Agent System for Facade		●				●			●									●		●							●		●		
29	2017	(Gerber, Pantazis, & Wang,		●			●				●									●					●				●				
30	2017	(Gerber, Pantazi, & Wang, Interactive Design of Shell		●				●				●										●					●						
31	2017	(Guon & Li, 2017)		●			●						●									●								●			
32	2018	(Pantazis & Gerber, A		●			●				●									●					●				●				
33	2018	(Ghaffarian, Fallah, & Jacob,		●			●						●	●								●									●		
34	2019	(Davide , Pilosof, Hadas ,		●			●							●								●											●
35	2019	(Agirbas, 2019)		●			●				●								●													●	
36	2019	(Pantazis, Environmental		●				●				●										●			●				●				
37	2020	(Smith, Danahy, & La Rotta,		●		●		●				●										●						●					
38	2020	(Fuchs & Neumayr, 2020)		●			●						●									●									●		

Table 1: Showing the list of Studied Papers.

Some questions and notions were raised in response to this literature review to be investigated further in detail. Such as what is the possible validation processes a user can do to guarantee and validate the work of MAS, he/she created. Most researchers count on the end product; if the end product is valuable and falls under their criteria, the process can be considered valid. The question here is how can research validate further these processes what other possible ways of validation for such uncontrolled environments of exploration are witnessed on the level of ABMS usage in creation. In addition, the notion of constraints, bias, and assumption. Can they offer a larger solution space or limit it, how the consequences of architects' bias and assumptions can be governed. With the intention to complexifies and yet produce exquisite forms the researchers adopt the concept of agent-based modeling and simulation in several levels such as manipulative level of agents that results into a form. The question here is how the design can be deliberate encompassing the architect's assumptions if ABMS gives and adapts an uncontrolled emergent phenomenon of exploration.

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