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Applications of Agent-Based Modeling (ABM) in Planning and Design of Built Environments

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Abstract: The modeling and simulation of built environments are crucial preliminary steps for their design, planning, and management. Among various simulation methods, agent-based modeling (ABM) has recently gained traction for simulating built environments due to its ability to effectively model and capture complex interactions between simulated entities. The increasing applications of ABM for the simulation of built environments necessitate a comprehensive review of past scientific endeavors with positive accomplishments and those that remain unsolved. This study seeks to address this gap by reviewing ABM and its applications in the simulation of built environments, with a specific focus on the planning and design phases. First, the research introduces ABM and its unique features concerning the simulation of built environments. Second, it conducts a systematic review of past studies in the planning (e.g., feasibility analysis, risk management, and scheduling under constraints) and design (e.g., automated design, collaborative design, improving operations, and facilitating evacuation) aspects of built environments. Finally, following the in-depth review and subsequent analysis, the study identifies the strengths and weaknesses of using ABM for simulating the built environments. The study concludes with a remark on potential future research directions to overcome the limitations of the existing studies.

Key words: agent-based modeling; ABM; built environment; design; planning

1. INTRODUCTION

Scientists have utilized a range of computer simulation tools to mimic real-world systems and gain insight into a variety of phenomena and situations. Recent advancements in hardware and software have greatly expanded research capabilities in exploring complex problems [1]. With respect to the built environment, this has resulted in simulation and modeling techniques that more closely resemble actual systems [2]. Agent-based modeling (ABM) is one such tool used in numerous studies related to the built environment [3]. In particular, researchers have shown significant interest in ABM's application to the planning and design of built environments over the past several years [3]. Despite its growing popularity among researchers, there remains a lack of comprehensive review research summarizing recent studies on ABM's application in built environments in light of recent powerful technological advances.

To address this gap, this research aims to provide a qualitative review of significant studies conducted over the last two decades on the applications of ABM in the planning and design of built environments. The review begins by providing an overview of ABM and its core components, as well as its distinguishing features, particularly in the context of built environments, in order to shed light on the primary reasons behind its recent surge in popularity. The review then categorizes the major applications of ABM in the field of planning and design of built environments and offers several examples of past studies in each category. Finally, the review identifies gaps in the research, outlines the limitations of ABM in the mentioned context, and offers several topics for future research to overcome these limitations and address gaps in previous research.

2. AGENT-BASED MODELING AND CHARACTERISTICS

An agent-based model (ABM) simulates agents interacting within an environment to predict potential emergent behavior [4]. The main components of ABM include agents, the environment they interact in, the rules governing their communicational, behavioral, and decision-making functions, and their interactions with each other and the environment [2]. Agents possess common features in ABM that include being purposive, autonomous, and adaptive [5].

In addition to individual agent features, ABM possesses several distinguishing features that provide unique benefits compared to other simulation techniques, such as discrete-event simulation (DES) and system dynamics (SD). One significant characteristic of ABM is its respect for the heterogeneity of agents, allowing for individual differentiation among agents within a group [6]. This enables more precise modeling and improves collective behavior, as oversimplification through homogenization may deviate outcomes from reality [7]. For example, according to a study on energy usage in buildings, energy consumption outcomes in buildings vary greatly based on the individual comfort preferences of each individual in a simulated built environment [8].

ABM also offers efficient solutions for multi-optional problems, generating almost every possible scenario due to its ability to differentiate each individual agent [9], [10]. While potentially computationally intensive, this bottom-up approach allows for exploring what-if questions without excessive assumptions or prearranged biases [11]. Furthermore, ABM can update agents' features spontaneously based on interactions, compared to other simulation methods with fixed states [12], allowing for a more realistic and accurate model. ABM's ability to explore a range of scenarios and update agent features over time makes it an ideal tool for seeking answers to complex problems more accurately and efficiently.

3. ABM APPLICATIONS IN BUILT ENVIRONMENTS

ABM has numerous applications in the built environment, spanning across several categories, including design, planning, waste management, and disaster management. Figure 1 shows the major applications of ABM in built environments.

1. **Design:** ABM can be used to simulate and optimize building systems and occupant behavior to improve energy efficiency and occupant comfort [8]. It can also enhance the design of our built environments to facilitate evacuation [13].
2. **Planning:** ABM can simulate complex systems and model interactions between agents and their environment. In regard to planning, ABM can be used to conduct feasibility analyses [14], predict and manage risks [15], and improve the scheduling of projects associated with developing our built environments [16].
3. **Waste Management:** ABM can simulate waste management systems and evaluate the impact of waste reduction strategies on waste generation and disposal. It can also simulate the behavior of individuals and groups in waste management systems and identify areas for improvement in waste reduction and recycling [17].
4. **Disaster Management:** ABM can simulate the behavior of individuals and groups during natural disasters or emergencies, helping planners and responders anticipate and mitigate potential risks. It can also evaluate the impact of emergency response strategies on agents' behavior and the overall system.

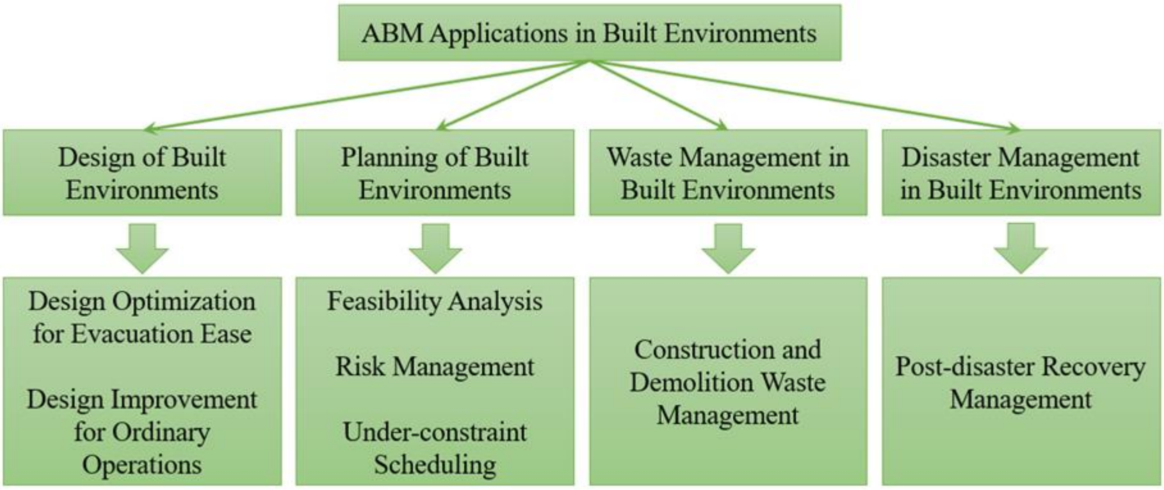

Figure 1. Major applications of ABM in built environments.

3.1. DESIGN OF BUILT ENVIRONMENTS

Ensuring safety during emergencies is crucial for any constructed facility in our built environments. While complying with building codes and regulations is necessary, it alone cannot guarantee that a design is fully satisfactory for emergency evacuations. To overcome this challenge, many researchers have turned to ABM to enhance building design for ease of evacuation during emergencies. Through computerized evacuation simulations, researchers can improve a facility's architectural layout and design for maximum evacuation efficiency. The accuracy in simulating human behaviors during egress is a critical factor, and ABM can reflect the heterogeneity in each individual's behavior, in addition to common herding and homogeneous behaviors.

Studies using ABM for design enhancement have followed two major trends. The first trend includes studies that aim to optimize facility design for ease of evacuation during emergencies. Researchers focus on facility type, architectural design variables in each facility, emergency events, and human characteristics to improve the design. For instance, one of the studies in this group aimed to optimize the size of doors and exits in a complex multi-room, multi-floor building [18], while another one focused on optimizing a building's exit width, door width, and corridor width in case of an indoor shooting incident [19].

The second trend of studies aims to improve facility design for better operation during ordinary periods. To account for varying and dynamic occupant behaviors and interactions with the building, researchers deploy ABM to acquire accurate estimations of a building's future status. Studies have centered on minimizing energy consumption while respecting occupants' preferences. For example, One of the studies in this group utilized ABM to offer an energy-efficient and occupant-pleasant building lighting design [20]. In contrast, another explored using daylight and artificial light in designing facade panels, seeking minimized energy consumption and occupants' satisfaction [21]. Also, two other studies deployed ABM to enhance the design of hospital facilities for better serviceability [22], [23].

3.2. PLANNING OF BUILT ENVIRONMENTS

Managing and scheduling activities in construction projects are challenging due to their dynamic nature and time, budget, and resource limitations. As a result, previous research has used agent-based modeling (ABM) to address these challenges, with studies categorized into three groups: feasibility analysis, risk management, and scheduling under constraints.

The first trend of studies used ABM to perform feasibility analyses of construction projects. These analyses consider various factors affecting the project's success and evaluate the feasibility of different approaches and financing strategies. ABM is useful because it can simulate different scenarios and their potential impacts on the project's success. For example, a study in this group used ABM and system dynamics to analyze project feasibility [24].

The second trend of studies focused on managing risks using ABM. Risks are an inevitable part of projects associated with developing our built environments and can interact with each other, making them difficult to manage. ABM has been used to identify potential risks, assess their impacts, test risk management strategies, and allocate risks among stakeholders. For instance, one of the studies in this group used ABM, along with a stochastic approach, to test various risk mitigation scenarios at both project and portfolio levels [25]. In contrast, another study applied a similar approach to detect and prevent risky scenarios in construction projects [26].

The third trend of studies used ABM to schedule projects related to creating our built environments. An effective schedule should account for time, budget, and resource limitations and address the proper allocation of resources to activities and the appropriate timing for implementing activities. ABM can reflect the specific features and uncertainties of each individual activity or resource, providing a flexible platform to seek alternative scheduling solutions. Past studies have used ABM to find an optimum project schedule under resource constraints, seek the most efficient scheduling for construction supply chains, and optimize resource allocation in various types of construction projects. A study in this group developed an agent-based model capable of automatically creating a detailed activity schedule [27], while another used ABM to allocate a limited budget among a portfolio of transportation projects [28].

3.3. WASTE MANAGEMENT IN BUILT ENVIRONMENTS

Waste management is a significant concern in our built environments due to the potential environmental impacts of leftover materials after the construction or demolition of built environments. Managing waste materials is complex due to the involvement of multiple stakeholders and various parameters. ABM can be used to model stakeholder interactions and test waste management strategies to move the system toward sustainable development. A few studies have used ABM for waste management in our built environments. One such study used ABM to investigate how stakeholders' attitudes towards project deconstruction and green management can mitigate the environmental impacts associated with waste management of urban projects [29]. An interesting study integrated ABM with optimization to simulate backfill supply chains and identify the most effective ways for backfill reuse and waste recovery [30]. Another study used ABM to analyze the factors impacting demand for recycled urban project materials and test strategies for incentivizing their use by the developers and constructors of our urban environment [31]. Furthermore, another study developed an ABM model with three agents to assess government policies for encouraging the construction industry to recycle used materials [32].

3.4. DISASTER MANAGEMENT IN BUILT ENVIRONMENTS

Unforeseeable disasters and emergency situations can lead to human loss and financial ruin. It is, therefore, vital for our built environments to have a comprehensive emergency management plan in place to reduce the impact of such incidents [33]. Developing emergency management plans using ABM has recently received significant attention. Various disasters and emergency situations may cause partial or complete devastation of our built environments. In such circumstances, the prompt recovery and re-establishment of damaged properties are critical for occupants, users, owners, and governmental agencies [34].

Furthermore, the post-disaster behavior of affected people and their decision-making processes may be different and more complicated than in normal situations. Consequently, some research studies have applied ABM to model these complex behaviors and interactions between the entities involved to explore effective building recovery plans. Although many research studies have been conducted on recovery plans using ABM, this review paper focuses only on those relevant to the construction field.

Many research studies in this group, such as [35], [36], aimed to develop an AB platform that automatically collects and integrates disaster information from various databases after disaster occurrence to provide responsible individuals and agencies with timely and necessary information and enable them to make prompt and appropriate decisions. Other studies, such as [37], [38], [39], developed AB models that can assist affected stakeholders and involved agencies and policymakers in reaching a consensus on the reconstruction and re-establishment of damaged facilities.

4. DISCUSSION

Despite the growing use of ABM in the planning and designing of our built environments, there are still notable gaps that present significant opportunities for further advamcenemtn of these valuable simulation techniques in this domain. The current study has identified several such gaps and proposes potential research topics for future studies in this area, including:

1. Applying ABM to automate operations in smart buildings: It involves simulating the actions and interactions of various elements, like HVAC, lighting systems, and occupants, to optimize and

automate building operations. This approach allows for efficient management, energy conservation, and enhanced comfort for occupants within the smart building ecosystem.

2. Further inclusiveness by taking into account various human behavioral features: Despite significant advances, recent models have accounted for limited human behavioral-related actions and interactions, which may lead to comparatively unrealistic outcomes. In the context of disaster management, for instance, accounting for further human-related behavioral actions and interactions may significantly change the simulation results.
3. Taking advantage of integrating ABM with other tools, such as BIM, in the context of built environments: More specifically, in the context of designing built environments, developing integrated ABM-BIM models can be of significant practicality due to their visualization power.

5. CONCLUSION

This study presented a qualitative review of the recent applications of ABM to our built environments. These applications were categorized into four main areas: design of built environments, planning of built environments, waste management in built environments, and disaster management in built environments. The study revealed that ABM has the potential to be beneficial in various fields as it considers the diverse behaviors of individuals towards facilities and their behavior changes over time. These distinctive attributes of ABM enable it to create multiple scenarios, evaluate their likelihoods, and predict the most plausible outcomes with great precision.

Despite such privileges, the applications of ABM to our built environments are yet to be further explored because the developed models lack several major points, especially with regard to inclusiveness. To tackle this challenge, developing comprehensive platforms through considering additional human-related features in interaction with each other was advised. These platforms can assist in mitigating the computational burden by combining different computational techniques that can efficiently handle the complex and extensive computations required by ABM. In addition, applying ABM to less-explored areas in the context of built environments, such as energy consumption optimization in green buildings and operations automation in smart buildings, can interest future research.

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