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Applications of Agent-Based Modeling (ABM) in Enhancing Facility Operation and Management

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Abstract: Agent-based modeling (ABM), as a relatively new simulation technique, has recently gained in popularity in the civil engineering domain due to its uniquely advantageous features. Among many civil engineering applications, ABM has been applied to facility operation and management, such as energy consumption management, as well as the enhancement of maintenance and repair processes. The former studies used ABM to manage energy consumption through simulating human energy-related behaviors and their interactions with facilities, as well as electrical, heating, and cooling systems and appliances, while the latter used ABM to enhance maintenance process through facilitating coordination, negotiation, and decision making between facility managers, service providers, and repair workers. The present study aims to provide a short qualitative review on the most recent applications of ABM in the above-mentioned areas. Based on the review and follow-up analysis, the study identifies the advantages, disadvantages, and limitations of ABM applications to facility operation and management, and offers several potential future research topics in the hope of filling the existing literature gaps.

Key words: agent-based modeling, simulation, facility management, energy, maintenance

1. INTRODUCTION

Researchers have leveraged various computer simulation tools to model actual systems and understand various phenomena/situations as the output of simulations. Recent technological advancements in both hardware and software have enhanced research capability and the boundaries of what computing techniques allow to explore in research problems [1]. In the civil/construction engineering domain, this has resulted in simulation/modeling techniques that more closely resemble actual systems [1]. Agent-based modeling (ABM), as one of these tools, has been used in various civil/construction engineering research studies [2]. In particular, ABM application in facility operations and management has gained significant attention by researchers over the past few years. Despite such growth and acceptance by researchers, the existing literature lacks a review research summarizing recent studies on ABM application in facility operations and management in relation with recent powerful technological advances.

To fill this gap, this research aims to provide a qualitative review on the most important studies conducted since 2000 on the applications of ABM in facility operations and management. The organization of this review is as follows. First, it describes ABM and its component elements along with its distinguishing features, especially in the context of facility operations and management, to reveal the main reasons behind its recent popularity. Then it classifies ABM's major applications in the area of facility operations and management, and provides a number of examples of past studies in different categories. Finally, it identifies their gaps, states ABM's limitations in the context of facility management, and proposes some frameworks for future research to overcome ABM's limitations and past research's gaps.

2. AGENT-BASED MODELING AND FEATURES

ABM is a modeling and simulation tool comprised of a set of entities (or agents) with their own behaviors and decision-making features [3]. Agents interact in a simulation environment to predict the potential collective behavior of the model as the main goal [4]. The major components of an agent-based (AB) model are: the agents; the environment within which the agents act; the rules that govern the agents' communication, behavior, and decision-making functions, and their interactions with each other and with their environment [5]. Agents, as the most significant components in ABM, typically have some common characteristics, which are listed in Table 1 [3]:

Table 1. Common features of agents in ABM and their implications

Agents' characteristic	Implication
Purposive	Having tasks to perform, and striving to cooperate and collaborate with other agents to move towards their targets
Autonomous	Being able to initiate activities without necessarily being triggered by external procedures, due to owning an independent and proactive nature
Adaptive	Perceiving dynamic situations which can impact their decision-making and behavioral features

Beyond the characteristics of individual agents, ABM has several unique features, as well as some advantages compared to other frequently used simulation techniques, such as system dynamics (SD) and discrete-event simulation (DES). Table 2 indicates the main distinguishing features of ABM, along with their brief explanations. One of the main differences relates to ABM's heterogeneous attitude towards agents. Other simulation tools commonly regard a system as homogeneous by attributing identical properties to all agents in a group, and governing identical interactional regulations over the agents' relations; however, ABM differentiates individual agents by attributing them varied features, and represents them as heterogeneous even if they fall inside the same group [3]. In the context of facility and operations management for instance, attributing the same energy-related behavior features to all occupants in a building may result in completely different energy consumption performance for the entire building, compared to when each occupant is assigned a unique feature. The oversimplification of a model following a homogeneous approach may significantly deviate the collective outcomes of the entire model from actuality, while ABM may provide more accurate results by taking into account the variety in agents' characteristics and behaviors.

The second distinguishing feature of ABM is its capability in adopting any specific convention over time progression. Unlike other simulation methods that fix the state of agents during an event, activity, or process, ABM is able to follow a continuous approach over the course of time, and updates the states of agents at any desired time interval. This feature allows AB models to reflect any changes in agents' status or features with the highest accuracy at any time and during any event, activity, or process over the course of simulation progression.

Table 2. Distinguishing features of ABM and their brief explanations

ABM's feature	Explanation
Adopting heterogeneity	Adopting a heterogeneous perspective and differentiating agents by attributing varied features
Agent updating	Adopting a continuous approach over time progression and updating agents' features at desired intervals
Scenario generation	Generating all possible scenarios and predicting the most probable outcomes with high accuracy

The third main difference between ABM and other simulation tools relates to ABM's capability in exploring optimized solutions for multi-optional problems [3]. ABM's power in differentiating each individual agent results in the generation of almost every potential scenario, which subsequently strengthens the possibilities of finding more efficient options. Unlike other simulation methods that test a prearranged hypothesis on the model by making excessive assumptions, ABM builds all potential scenarios, measures their possibilities, offers the most probable scenarios, and averages the model's outcomes.

3. ABM APPLICATIONS IN FACILITY OPERATION AND MANAGEMENT

It is critical for a constructed facility to fulfill its intended application during its entire expected lifetime span [6]. Each facility requires a comprehensive management and maintenance plan to provide services to its occupants/users continuously and efficiently. Such a plan should diagnose and prognose operating issues, and control them in a timely and appropriate manner [7]. The plan should also account for occupants or users' maximum comfort and satisfaction, along with the facility's energy-efficient performance [8]. Many studies have taken advantage of simulation tools to offer post-construction management and maintenance plans. A critical factor in such simulations is the accuracy of occupants'/users' behaviors, their interactions with a facility, and their attitudes towards a facility's serviceability to those of real-world occupants and users. ABM can account for variety in users'/occupants' behaviors by regarding them as heterogeneous individuals. ABM can also respect their varying behaviors during a facility's lifetime span by following any specific desirable convention (either continuous or discrete) over the course of time progression. Hence, many research studies have deployed ABM to enhance the operation and maintenance of facilities over the post-construction period. In this context, the two areas within which ABM has the most applicability are: 1) energy consumption management; and 2) maintenance and repair.

3.1. ABM in energy consumption management

Different human beings show varied energy-related interactional behaviors towards different facilities and their electrical, heating, and cooling systems and appliances. In addition, such interactional behaviors vary over time after interacting with the facility and other humans. ABM has the capability of accounting for varied and varying energy-related behaviors of humans over the course of time. Past studies on this subject have benefited from such ABM's strengths to simulate human behaviors in facilities. Figure 1 demonstrates the main steps of using ABM in energy consumption management.

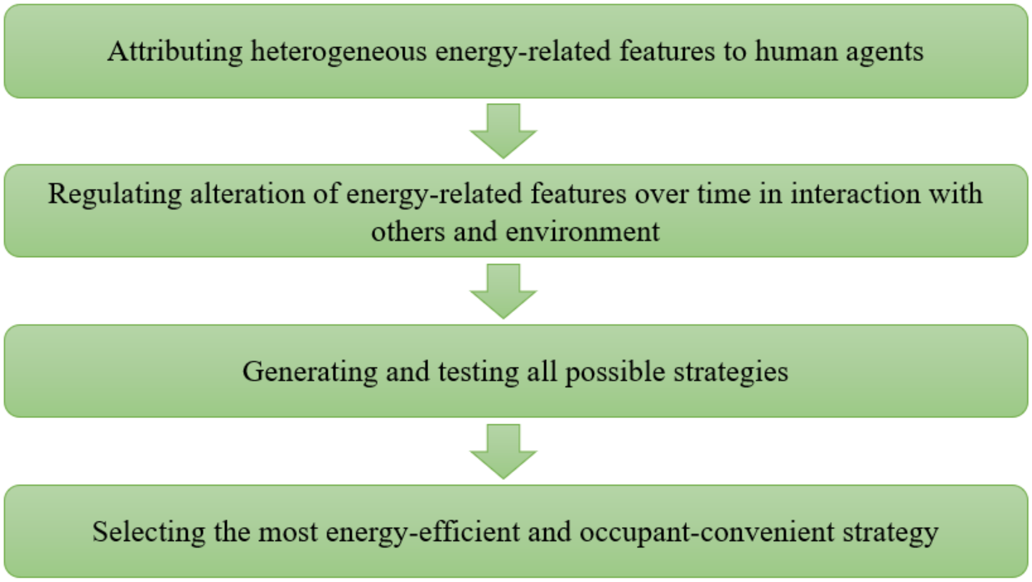

Figure 1. Steps of applying ABM to energy consumption management

Most studies have utilized ABM to evaluate various energy saving strategies and policies in different types of facilities. For instance, Zhao et al. [9] developed an agent-based (AB) decision making model to optimize the generation and distribution of energy in a building, while Ding et al. [10] assessed various energy-saving scenarios in student residences, such as student awareness increases, or reward-and-punishment system implementation, considering the fact that occupants' energy-related behaviors in shared places may significantly differ from those in private places. Similarly, Zhang et al. [11] evaluated various energy management strategies in an office building by focusing on energy management technologies and organizational policies. Also, Liang et al. [12] assessed the effectiveness of various governmental energy-efficiency incentive strategies in decreasing energy consumption, and found that the government can incentivize owners by paying special attention to energy prices. In another research, Norouziasl et al. [13] used occupancy sensors to predict personnel schedules and their lightning-related behaviors in an office building, simulated such an environment through ABM, and finally investigated an efficient approach to reduce lightning energy consumption.

In addition to energy consumption reduction, some studies attempted to improve occupants' comfort as another critical factor. For instance, Klein et al. [14] developed an AB model that promotes energy efficiency by scheduling meetings and controlling building systems, while at the same time attempts to improve occupants' comfort. Other studies used ABM to develop a facility management plan that reduces energy consumption, while improving occupants' wellbeing and thermal comfort [15], [16]. Another unique aspect of their research was considering the movements of people between a group of buildings, rather than a single building, and their social engagement with multiple people, which makes their model applicable for large-scale communities, such as university campuses.

3.2. ABM in maintenance and repair

The failure of a facility's systems may result in financial loss and user dissatisfaction. Hence, predicting probable failures and reducing response times in solving maintenance problems, along with maintaining a facility's serviceability during reparations are among the substantial issues on this topic [17]. To overcome these issues, past studies have utilized ABM combined with auxiliary tools such as sensors, to develop maintenance and repair frameworks. Figure 2 shows the main steps of applying ABM to solve maintenance and repair problems.

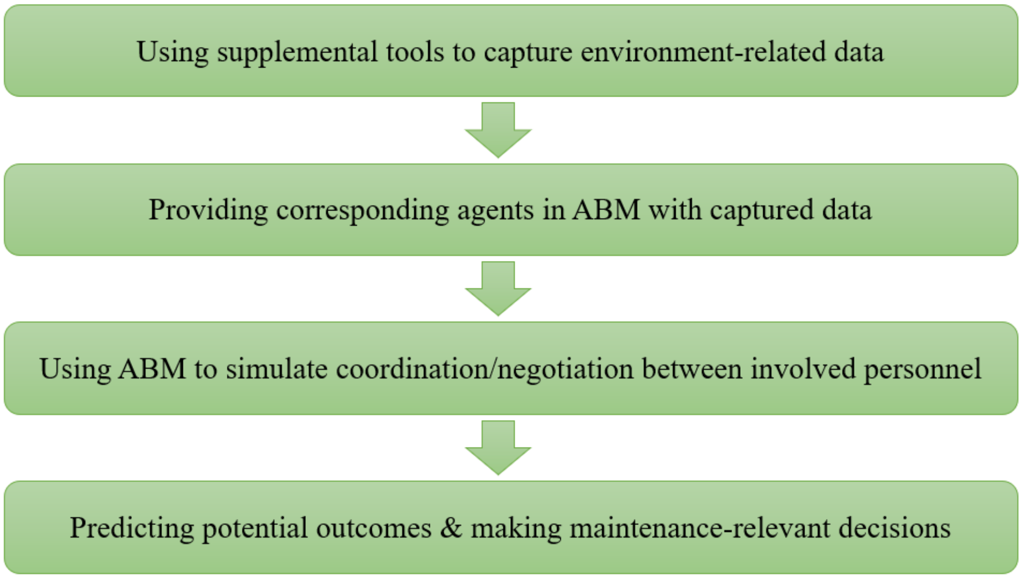

Figure 2. Steps of applying ABM to maintenance and repair management

Past studies applied sensing technologies to collect real-time data in order to predict or detect potential operating problems, and then applied ABM subsequently to systemize the collected data to facilitate the coordination, negotiation, and decision-making processes for facility managers, service providers, and repairmen. As an instance, Shen et al. [18] developed an AB platform in integration with building information modeling (BIM) and sensing technologies, which collects relevant data during all facility lifecycle stages, and uses them to optimize the decision-making process associated with the maintenance of a facility. Similarly, [7] used ABM in integration with sensing technologies and game theory to develop a collaborative maintenance decision support platform. Other research studies [19], [20] applied ABM to solve road-maintenance-related decision making problems. While Yu et al. [18] attempted to enhance the quality of road maintenance services by reducing travel time, taking into account different traveler perception levels and interactions between cars, Denisov et al. [20] offered a plan for the efficient use of road-maintenance equipment units. In addition, Yousefli et al. [17] developed a decentralized maintenance management platform with the help of ABM to reduce the response time to maintenance orders in a healthcare facility.

4. GAPS, LIMITATIONS, AND FUTURE DIRECTIONS

Despite having several advantageous and distinguishing features, ABM application in facility operations and management has several limitations. One of the ABM's major limitations in this context pertains to the computational aspect. Facilities and their operations are dynamic due to the multitude and instability of involved factors, accounting for all of which, through attributing varying features to various agents, imposes an outrageous level of computations, at the cost of raising the accuracy of the final model's outcomes. Despite the recent advancements in computing tools, it might be still difficult to utilize ABM with its highest detail levels when the magnitude or duration of model under-study raises. Therefore, a potential topic for future studies can be exploring a tradeoff between model accuracy and computational burden. As an instance, further frameworks can be developed by following a semi-heterogeneous architecture, which can identify factors whose heterogeneity has minimal impact on the model's final outcomes, and regards them as homogeneous in the model. Such frameworks could make the models time-efficient and raise their practicality and applicability for solving real-world facility and operations management problems of real size.

Another common issue with ABM studies in this context is their authentication. Researchers have developed models based on a set of theoretical equations and regulations determining how humans behave and interact with one another, and how their behaviors and interactions change over time. While the model outputs heavily depend on such equations and regulations, past research has not paid sufficient attention to their validity. Therefore, future research should aim to verify such equations via empirical-based real-world cases, e.g., by collecting data from the constructed facilities that are being simulated. Collecting such data through using sensors [13], cameras or mobile devices can significantly enhance the validity of the models if accurately reflected inside the equations and regulations.

Another direction for potential future research could be the enhancement of real-time management models. Sensors are useful tools in both providing authentic inputs to the model along with feeding decision-making agents with real-time data. Integration of ABM, due to its respect to heterogeneity, with real-time data captured by sensors can strikingly increase operations management efficacy because of high customization level. In addition to sensing technologies, the ABM integration with other tools could gain attention in future studies. For instance, ABM-BIM models, due to their visualization power and their capability in offering detailed information on a facility's elements, can be of increasing research interest. Moreover, as ABM can provide near-real time solutions, its integration with optimization techniques could help in achieving greater optimality levels, especially in the context of energy consumption management.

Finally, another problem in this context is the demand for developable platforms. Many researchers developed various models separately, each of which indicates a distinctive behavioral and decision-making regulations towards human behaviors and interactions, but they are not open-source, accessible by public, and modifiable. Future researchers should take this point into account to avoid repetitive activities, and to benefit other researchers by continuing their research from the most cutting-edge and updated point. There is a significant need for future research to develop a generalized AB open-source library encompassing humans' behavioral and interactional features in relation with facility and operations management.

5. CONCLUSION

This study offered a qualitative review on the recent applications of ABM in the context of facility and operations management. These applications were categorized into two main areas, including energy consumption management and facility maintenance and repair. The research demonstrated that the application of ABM in such areas can be useful since ABM accounts for not only the heterogeneity of humans' behaviors in relation with facilities, but also the variation in their behaviors over the course of time. Such distinguishing and beneficial features allow ABM to generate almost all potential scenarios, measure their possibilities, and project the most probable outcomes with a high level of accuracy.

Despite such privileges, the application of ABM to facility operations and management problems can impose outrageous computational burden, which may limit its practicality for large-scale or long-duration problems; to overcome this, the development of semi-heterogeneous platforms was recommended. Additionally, the previous models have been mostly developed based on a set of equations without powerful authentications. To address this drawback, the use of sensors for data collection and empirical verification of regulatory equations was introduced. In addition, the research suggested further research on the integration of ABM with sensing technologies, BIM, and optimization techniques for real-time management of a facility's operations, obtaining better visualization, and achieving higher optimal outcomes, respectively, as other potential research areas. Finally, the development of general, open-source, and editable libraries encompassing facility-related human behavioral and interactional features was suggested.

REFERENCES

[1] A. Jabri and T. Zayed, "Agent-based modeling and simulation of earthmoving operations," *Automation in Construction*, vol. 81, pp. 210–223, 2017, doi: 10.1016/j.autcon.2017.06.017.

[2] A. Khodabandelu, J. W. Park, and C. Arteaga, "Crane operation planning in overlapping areas through dynamic supply selection," *Automation in Construction*, vol. 117, no. April, p. 103253, 2020, doi: 10.1016/j.autcon.2020.103253.

[3] A. Khodabandelu and J. W. Park, "Agent-based modeling and simulation in construction," *Automation in Construction*, vol. 131, no. August, p. 103882, 2021, doi: 10.1016/j.autcon.2021.103882.

[4] C. Macal and M. North, "Introductory tutorial: Agent-based modeling and simulation," in *Proceedings of the Winter Simulation Conference 2014*, 2014, pp. 6–20. doi: 10.1109/WSC.2014.7019874.

[5] E. Bonabeau, "Agent-based modeling: Methods and techniques for simulating human systems," *Proceedings of the National Academy of Sciences*, vol. 99, no. suppl 3, pp. 7280–7287, 2002, doi: 10.1073/pnas.082080899.

[6] A. Shekargoftar, H. Taghaddos, A. Azodi, A. Nekouvaght Tak, and K. Ghorab, "An Integrated Framework for Operation and Maintenance of Gas Utility Pipeline Using BIM, GIS, and AR," *Journal of Performance of Constructed Facilities*, vol. 36, no. 3, pp. 1–17, 2022, doi: 10.1061/(asce)cf.1943-5509.0001722.

[7] A. J. C. Trappey, C. V. Trappey, and W. C. Ni, "A multi-agent collaborative maintenance platform applying game theory negotiation strategies," *Journal of Intelligent Manufacturing*, vol. 24, no. 3, pp. 613–623, 2013, doi: 10.1007/s10845-011-0606-5.

[8] M. Sadat-Mohammadi, M. Nazari-Heris, E. Nazerfard, M. Abedi, S. Asadi, and H. Jebelli, "Intelligent approach for residential load scheduling," *IET Generation, Transmission and Distribution*, vol. 14, no. 21, pp. 4738–4745, 2020, doi: 10.1049/iet-gtd.2020.0143.

[9] P. Zhao, S. Suryanarayanan, and M. G. Simoes, "An energy management system for building structures using a multi-agent decision-making control methodology," *IEEE Transactions on Industry Applications*, vol. 49, no. 1, pp. 322–330, 2013, doi: 10.1109/TIA.2012.2229682.

[10] Z. Ding, T. Hu, M. Li, X. Xu, and P. X. W. Zou, "Agent-based model for simulating building energy management in student residences," *Energy and Buildings*, vol. 198, pp. 11–27, 2019, doi: 10.1016/j.enbuild.2019.05.053.

[11] T. Zhang, P. O. Siebers, and U. Aickelin, "Modelling electricity consumption in office buildings: An agent based approach," *Energy and Buildings*, vol. 43, no. 10, pp. 2882–2892, 2011, doi: 10.1016/j.enbuild.2011.07.007.

[12] X. Liang, T. Yu, J. Hong, and G. Q. Shen, "Making incentive policies more effective: An

agent-based model for energy-efficiency retrofit in China," *Energy Policy*, vol. 126, no. November 2018, pp. 177–189, 2019, doi: 10.1016/j.enpol.2018.11.029.
[13] S. Norouziasl, A. Jafari, and C. Wang, "An agent-based simulation of occupancy schedule in office buildings," *Building and Environment*, vol. 186, no. October, p. 107352, 2020, doi: 10.1016/j.buildenv.2020.107352.
[14] L. Klein *et al.*, "Coordinating occupant behavior for building energy and comfort management using multi-agent systems," *Automation in Construction*, vol. 22, pp. 525–536, 2012, doi: 10.1016/j.autcon.2011.11.012.
[15] E. Azar and H. Al Ansari, "Multilayer Agent-Based Modeling and Social Network Framework to Evaluate Energy Feedback Methods for Groups of Buildings," *Journal of Computing in Civil Engineering*, vol. 31, no. 4, pp. 1–14, 2017, doi: 10.1061/(ASCE)CP.1943-5487.0000651.
[16] E. Azar, C. Nikolopoulou, and S. Papadopoulos, "Integrating and optimizing metrics of sustainable building performance using human-focused agent-based modeling," *Applied Energy*, vol. 183, pp. 926–937, 2016, doi: 10.1016/j.apenergy.2016.09.022.
[17] Z. Yousefli, F. Nasiri, and O. Moselhi, "Maintenance workflow management in hospitals: An automated multi-agent facility management system," *Journal of Building Engineering*, vol. 32, no. December 2019, p. 101431, 2020, doi: 10.1016/j.jobe.2020.101431.
[18] W. Shen, Q. Hao, and Y. Xue, "A loosely coupled system integration approach for decision support in facility management and maintenance," *Automation in Construction*, vol. 25, pp. 41–48, 2012, doi: 10.1016/j.autcon.2012.04.003.
[19] B. Yu, Z. Guo, Z. Peng, H. Wang, X. Ma, and Y. Wang, "Agent-based simulation optimization model for road surface maintenance scheme," *Journal of Transportation Engineering Part B: Pavements*, vol. 145, no. 1, pp. 1–9, 2019, doi: 10.1061/JPEODX.0000097.
[20] M. V. Denisov, A. V. Kizim, A. V. Matokhina, and N. P. Sadovnikova, "Repair and maintenance organization with the use of ontologies and multi-agent systems on the road sector example," *World Applied Sciences Journal*, vol. 24, no. 24, pp. 31–36, 2013, doi: 10.5829/idosi.wasj.2013.24.itmies.80006.