ENGLSH VERSION..

Agent based modeling: a tool for construction engineering and management?

Modelación basada en agentes: ¿una herramienta para la ingeniería y gestión de la construcción?

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Abstract

Construction projects represent complex systems where the interactions between the multiple project resources and stakeholders change over time; however, traditional methods to manage construction projects typically cannot capture such complexity in its totality. Thus, limiting our understanding of such complexity on construction projects. A novel approach used to investigate complex adaptive systems, Agent-based modeling (ABM), allows modeling the interaction between multiple agents that leads to emergent behaviors. As such, this approach represents a feasible modeling technique to study the inherent complexity of construction projects by spending computing resources instead of actual resources, which can be more cost-effective. However, limited attention has been paid to this modeling technique in the construction and management field. This paper aims to discuss guidelines for implementing ABM in the construction sector by discussing its benefits and limitations. It was found that ABM allows the incorporation of otherwise unaccounted complexity associated with construction processes and projects. However, a limitation of ABM is that data to validate models can be difficult to obtain. It is expected that this study helps to encourage the use of ABM in the context of the construction engineering and management field to fully capture the complexity of construction projects and processes.

Keywords: *Agent-based modeling; construction engineering and management*

Resumen

Los proyectos de construcción representan sistemas complejos donde las interacciones entre los múltiples recursos del proyecto y las accionistas cambian con el tiempo; sin embargo, los métodos tradicionales para administrar proyectos de construcción generalmente no pueden hacerse cargo totalmente de tal complejidad, limitando nuestra comprensión de tal complejidad en los proyectos de construcción. Un enfoque novedoso utilizado para investigar sistemas adaptativos complejos, es la modelación basada en agentes (MBA), esta permite modelar la interacción entre múltiples agentes que conducen a comportamientos emergentes. Como tal, este enfoque representa una técnica de modelaje factible para estudiar la complejidad inherente de los proyectos de construcción al gastar recursos informáticos en lugar de recursos reales, que pueden ser más rentables. Sin embargo, se ha prestado una atención limitada a esta técnica de modelado en el campo de la construcción y la gestión, este documento tiene como objetivo discutir las pautas para implementar MBA en el sector de la construcción, discutiendo sus beneficios y limitaciones. Se descubrió que MBA permite la incorporación de la complejidad no contabilizada asociada con los procesos y proyectos de construcción. Sin embargo, una limitación de MBA es que los datos para validar modelos pueden ser difíciles de obtener, se espera que este estudio ayude a fomentar el uso de MBA en el contexto del campo de ingeniería y gestión de la construcción para capturar completamente la complejidad de los proyectos y procesos de construcción.

Palabras clave: Modelación basada en agentes; construcción ingenieria y administración

1. Introduction

Construction projects involve multiple participants (e.g., owner, designer, contractor, subcontractors) in a dynamic environment during a project's lifecycle, which influence the behavior of all the project' participants, and as such, construction projects have been identified as complex systems (Walsh et al., 2003). Complex systems exhibit what is referred to as emergent behaviors, which results from the interaction between system components and cannot be explained by the understanding of the individual components only (Bernhardt and McNeil, 2008); (Macal and North, 2010); (Watkins et al., 2009). For instance, the productivity in the construction site has been defined by the interaction among individual crew members, labor crews, and the tasks defined by the schedule and resource constraints (Watkins et al., 2009).

Multiple studies have emphasized the notion that existing modeling approaches used in the construction projects lack the ability to capture inherent complexities associated with construction projects, such as project fragmentation and collaboration (Bernhardt and McNiel, 2008); (Liang et al., 2016); (Zhu and Mostafavi, 2017). Interestingly, a modeling approach that has been suggested as capable of overcoming this limitation is agent-based modeling (Hsu et al., 2016); (Osman, 2012); (Liang et al., 2016); (Zhang et al., 2019).

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Agent-based modeling (ABM) is a bottom-up approach that allows studying how system rules and patterns emerge from the individual behavior of agents, as such, ABM accounts for the heterogeneity of each agent and allows agents to evolve and adapt to the conditions of its environment (Watkins et al., 2009). Existing studies have applied ABM in construction projects in different contexts. For instance, to better understand projects' stakeholders (e.g., managers, workers; (Hsu et al., 2016); (Ahn and Lee, 2015), construction stages (e.g., site operations; (Watkins et al., 2009)), and the inherent complexity of infrastructure projects (Osman, 2012). Ultimately, in multiple studies, it is concluded that efforts should be pursued to expand the use of ABM to the construction industry as the full complexity observed during the execution of a project can be analyzed using the ABM approach (e.g., (Liang et al., 2016); (Ren and Anumba, 2004). However, it has also been recognized that due to the high complexity of problems in the construction industry, the successful expansion and implementation of ABM in construction requires guidelines to facilitate its use for researchers and practitioners (Liang et al., 2016); (Ren and Anumba, 2004).

As such, this study aims to assess and discuss the existing literature regarding ABM applications to propose recommendations and guidelines for future implementations of ABM in construction projects. Ultimately, this study may facilitate the use of ABM for construction researchers and practitioners to take advantage of this novel technique to analyze and better understand the complexity of construction projects.

2. Background research

This section discusses the concepts of agent-based modeling as a method, and then different applications found in the construction engineering and management literature.

2.1 Agent-Based Modeling

Agent-based modeling is an approach to model complex systems composed of individual elements (i.e., agents), which have the ability to interact under the same environment (Macal and North, 2010). Agents have individual behaviors that are represented through a set of rules and give the ability to fully represent the diversity and heterogeneity of the multiple agents involved in a system. Moreover, as these heterogeneous agents are capable of interacting under the same environment is that the systemic behavior emerges (Bonabeau, 2002); (Macal and North, 2010). Precisely, these two characteristics, the emphasis on modeling agents' heterogeneity and emergent behaviors are distinguished features of ABM as modeling technique compared with other methods, such as discrete event simulation (DES) or system dynamics (SD) (Macal and North, 2010). Ultimately, the goal of ABM is not to optimize a complex system but to understand the process that may emerge in such a complex system. (Figure 1) shows a representation of how agents and their behavior contribute to the system's emergent behavior.

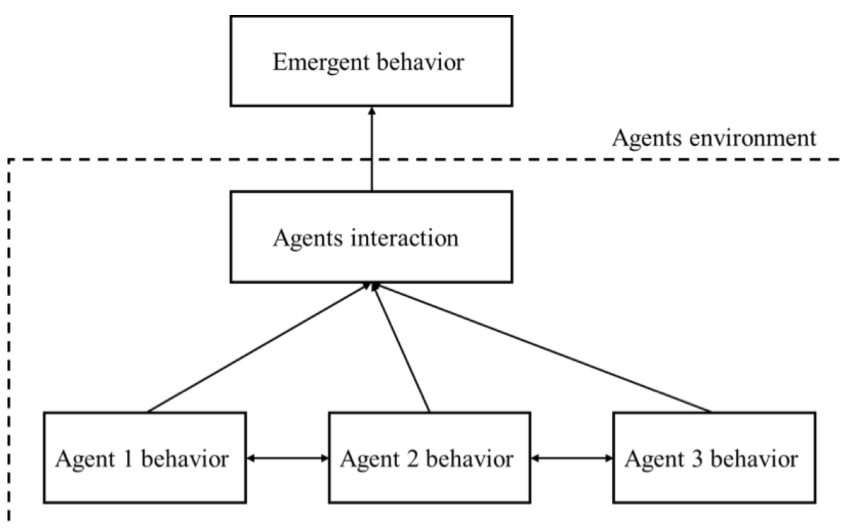

Figure 1. *Agents' interaction contributing to system emergent behavior (own elaboration).*

When it comes to the contexts in which ABM is (is not) recommended to be used, it has been emphasized that when clear governing laws of physics exist, the system under study cannot operate if one component is taken out, or uncertainty governing system equations are very low, ABM is not recommended to be implemented. Conversely, if human behavior is an important factor in the system (e.g., learning and adapting), independently operating entities under uncertainty exist, and economic, social, or political factors are involved, ABM is recommended to be implemented (Macal and North, 2010); (Walsh et al., 2003). Applications of ABM span multiple areas and disciplines, such as biology, ecosystem, and environmental management, water resource management, social sciences, and construction management (Echaveguren et al., 2017); (Grigoryev, 2012); (Hogeweg and Hesper, 1983); (Lansing and Kremer, 1993); (Liang et al., 2016); (Yazdani et al., 2015). Ultimately, the implementation of ABM in the field of construction engineering and management is the focus of the next section.

2.2 ABM in construction

Multiple studies have implemented ABM in the context of construction engineering and management. The main argument presented in the literature to implement ABM is that the bottom-up approach of modeling agents (e.g., workers from a work crew) from construction processes facilitates the understanding of the inherent complexity related to such processes. Interestingly, processes involved throughout the different stages of the lifecycle of construction projects have been modeled using ABM, for instance, labor efficiency as an emergent behavior from individual and crew interactions during construction operations (Watkins et al., 2009). In terms of organizing the existing studies implementing ABM in construction engineering and management, (Osman, 2012) suggested that studies span five categories: site operations, claims and negotiations, resource allocations, supply chain management, and infrastructure management. More recently, researchers have combined ABM with other simulation techniques in construction, such as building information modeling (BIM), and as such, a sixth category encompassing ABM and BIM is discussed as well. In the following paragraphs, existing studies related to these six categories are discussed.

2. 2.1 Site Operations

Regarding site operations, (Watkins et al., 2009) implemented an agent-based model to study the construction site as a complex system focused on the individual and crew interactions to model labor productivity as an emergent property of the system. The model proposed by Watkins and colleagues provided an alternative bottom-up approach to understand labor efficiency compared to the top-down approaches to the modeling of labor efficiency. When it comes to the modeling of site operations involving equipment, (Jabri and Zayed, 2017) developed an agent-based earthmoving model that allowed to model equipment units (e.g., bulldozers, loaders, haulers) with different specifications performing the same task (e.g., tracks with different capacities), which allowed to assess the interaction of different equipment for earthmoving tasks. More importantly, the proposed model allowed authors to account for special earthmoving operation scenarios of resource constraints.

2.2.2 Claims and Negotiations

The process of negotiation among multiple parties in construction fits well with the agent-centric approach of ABM. Negotiation parties can be understood as autonomous agents that have different and many times conflicting objectives (Ren et al., 2003). As such, existing studies have been focused on modeling the construction negotiation process. For instance, (Ren et al., 2003) implemented an ABM approach to model the negotiation process focused on agents' learning process. Similarly, (El-Adaway and Kandil, 2010) proposed a dispute resolution system using ABM, which was calibrated using 30 arbitrated construction disputes. Interestingly, the study results showed that the proposed system was able to generate legal arguments while preparing the defense of different positions on the arbitration. Consequentially, saving time and efforts to dispute professionals related to construction claims and disputes.

2.2.3 Resource Allocations

When it comes to the resource allocation from the owner's perspective, Farschian and colleagues have implemented ABM models to study the problem of budget allocation in the portfolio of projects (Farshchian et al., 2017), and the problem of uncertainty related to the portfolio of projects (Farshchian and Heravi, 2018).

In the realm of resource allocations during construction projects, (Yang and Mohamed, 2008) proposed a multi-agent resource allocation (MARA) model in the context of industrial construction assembly processes. Similarly, (Taghaddos et al., 2012) implemented a multi-agent resource allocation (MARA) model for the problem of scheduling resources in a large construction project. Interestingly to notice, the implementation of agent-based *models has been proposed to overcome existing limitations of existing scheduling techniques in construction projects (e.g., CPM), such as capturing the dynamic and uncertain nature of construction projects (Taghaddos et al., 2012).*

2.2.4 Supply Chain

Concerning the modeling of the construction supply chain using ABM, (Xue et al., 2005) proposed a model to study the coordination of the construction supply chain through a multi-attribute negotiation mechanism represented through agents. More recently, (Gan and Cheng, 2015) proposed an agent-based modeling approach to analyze the supply chain of backfill in construction waste management; furthermore, the authors developed an optimization model to be compared with the agent-based model. Interestingly, (Gan and Cheng, 2015) found that the ABM approach fits better to study the dynamic backfill supply chain due to the capabilities of ABM to quickly adapt to unexpected model modifications and the decentralized approach of the model.

2.2.5 Infrastructure Management

When it comes to the modeling approaches regarding the management of infrastructure, it has been claimed that traditionally decision-making approaches have not been able to represent complexities from the infrastructure management process, for example, during the maintenance of infrastructure (Bernhardt and McNeil, 2008); (Osman, 2012).

Probably, due to our limited understanding of the complex process of managing infrastructure is that we have observed the deterioration of existing infrastructure over time; for example, in the United States, their existing infrastructure has been graded as poor in recent decades (ASCE, 2013); (ASCE, 2017). This context has forced researchers and practitioners to look for new methods to manage infrastructure. Interestingly, multiple studies have claimed that the implementation of ABM to manage infrastructure can address this limitation (Bernhardt and McNeil, 2008); (Osman, 2012). (Osman, 2012) presented an ABM framework to study the interactions between infrastructure users, assets, operators, and politicians. The main contribution was to demonstrate the applicability of using agent-based modeling to represent complex interaction among multiple stakeholders involved in the management of urban infrastructure. Similarly, (Yazdani et al., 2015) proposed a framework to understand the role of coordination between the multiple agencies involved in the provision of urban infrastructure to new urban areas. More recently, ABM has also been implemented in the context of managing urban infrastructure in response to migratory disasters. More specifically, in the context of the European refugee crisis, (Araya et al., 2020) assessed the role of communities hosting displaced populations in the provision of urban infrastructure to such displaced persons.

2.2.6 ABM and BIM.

In recent years, researchers have begun to expand the use of ABM in the realm of construction engineering and management with technologies already in place in the construction industry, such as building information modeling—BIM (Cheng et al., 2018); (Micolier et al., 2019). BIM is a collection of visualized building information, and as such, BIM models facilities without accounting for human behavior (Porter et al., 2014). Therefore, the integration of ABM and BIM can improve the performance of analyses using BIM by providing a simulation of the interaction between humans and the building (Liang et al., 2016).

(Shi et al., 2009) proposed an agent-based model to study the occupant behavior from a public building (i.e., indoor stadium) under a fire scenario. From the results of the model, then a model for fire evacuation was finally proposed by the authors. Similarly, (Cheng et al., 2018) developed a model combining BIM and ABM to simulate different evacuation plans on offshore oil and gas platforms (OOGPs). The multiple simulations with the proposed model allowed to assess different evacuation plans to improve the performance of evacuations on OOGPs; furthermore, the authors concluded that the model was more than transferable to other industries in need of more evacuation planning research, such as the engineering and construction industry (Cheng et al., 2018). When it comes to the interaction between ABM and BIM in residential environments, (Micolier et al., 2019) proposed a model accounting for multiple residents' attributes (e.g., social-behavior, thermal model, comfort model, decision-making model) interacting with the BIM model. Notably, the proposed model enabled the study of the impact of building designs on occupants' comfort and the influence of occupants' behavior on building performances (Micolier et al., 2019).

Researchers also have implemented agent-based modeling to assess the adoption of BIM in construction projects. Specifically, accounting for the social interactions of participants involved during BIM-based design. (Al Hattab and Hamzeh, 2018) modeled the social aspects of people's interaction with the exchanged information when adopting BIM in a project. Interestingly, the authors' main finding was that the implementation of BIM does not directly result in a better design process (e.g., better quality). Conversely, the successful implementation of BIM is highly dependent upon how the organization and its members adopt BIM; attributes from the organization and its *members that are desirable to implement BIM were collaboration and having an open mindset to do things differently than using traditional approaches (Al Hattab and Hamzeh, 2018).*

3. ABM the path to better understand construction projects?

As discussed in this study, methods typically used to model construction environments have fully captured the inherent complexities of construction projects. As such, there is a need to search for new techniques that can overcome such existing limitations in the construction engineering and management (CEM) field. That is how, in recent years, the agent-based modeling (ABM) approach has been implemented by multiple CEM researchers and practitioners, getting promising results regarding the modeling of construction projects and its processes. In general, it has been found that implementing the agent-based modeling (ABM) approach provides multiple benefits for the construction engineering and management (CEM) field, namely by modeling the construction environment as a complex system that allows identifying otherwise undetected emergent behaviors from the system. Nonetheless, the implementation of ABM in CEM has also identified some limitations. (Table 1) shows the main findings and limitations identified in the literature review prepared in this study. The following sections discuss the main benefits, limitations, and the path ahead for the implementation of ABM in the CEM field.

Table 1. *Summary of the benefits of implementing ABM in construction engineering and management.*

Authors	Main findings	Limitations
Watkins et al. (2009)	Crew interaction included in construction planning accounting for workers congestion	Model assumptions are not fully representative of real conditions in construction projects
Osman (2012)	The interaction between infrastructure users, engineers, managers, and decision-makers can be accounted for in the management of infrastructure	Modeling individual behavior of model agents accurately
Ran and Anumba (2004)	ABM is naturally suited for the construction industry due to its fragmented nature	The learning ability of agents is fundamental to adapt given the always-changing environment of construction
Micolier et al. (2019)	ABM allows to model human behavior in residential buildings that can be used as an input for BIM models	Human behavior may be subject to cultural preferences, and as such, it may vary among different geographic locations
Liang et al. (2016)	Autonomous, cooperative, and learning attributes from agents supports the study of collaboration and consensus in construction projects	From the industry perspective, ABM is not a must-have tool yet

3.1 Benefits of using ABM in Construction

Based on the literature reviewed in this study, the use of ABM in the construction engineering and management field represents an incremental step in capturing the complexity of construction projects as a system. Such complexity comes primarily from the bottom-up modeling approach that allows studying individuals involved in the construction process (e.g., crew members). In other words, better modeling of the individual elements involved in construction projects during the different phases of a project's lifecycle allows having a better understanding of construction projects. Such an understanding of construction projects elements at the individual level represents a benefit for construction managers in the sense that by better understanding these individual elements—i.e., agents—managers can develop and implement more specific plans and programs to improve construction projects' performance. For example, having a better understanding of the specific role of crew *members and their interactions on productivity may help foremen and project managers in designing productivity improvement programs that are more specific at the worker or crew level.*

Another benefit of using ABM is the interactive and evolving nature of ABM models. Given that the system's behavior is simulated based on the behavior of the individual components of the system under study, emergent and often unexpected behaviors can be identified. More importantly, such unexpected behaviors can be eventually be included in future versions of models, so the modeling process of the system under study is closer to represent the real conditions of the system under study. Important to notice is that ABM is not an optimization tool; it is a simulation tool to understand the complexity of systems under study; for instance, it is possible to develop what-if scenarios.

Similarly, another benefit of using ABM is that it facilitates the inclusion of multiple stakeholders involved in the management of construction projects. Namely, in infrastructure projects, the role of local communities has often been neglected, in which multiple cases have had negative consequences for such projects—e.g., project budget increase and halted projects. Specifically, in infrastructure projects, which have a much higher social component compared with private construction projects, the role play by local communities impacted by the development of infrastructure projects is a line of research that needs more studies to be undertaken, and as such, ABM provides an excellent tool to do so (Osman, 2012).

Finally, although not explicitly said in the literature, the author of this study suggests that one of the main contributions of implementing ABM in the field of construction engineering and management (CEM) may come from the fact that to develop a model, it is necessary to have principles, a theory, and data that supports the development of such model. As such, researchers are starting to expand existing models and data available in the CEM field who can enrich our understanding of it. More importantly, it is not only that more data is now becoming available with the development of agent-based models, but also the level of data granularity allows CEM researchers to have a much better understanding of individual elements involved in construction projects, such as crew workers, and incorporate these elements in the modeling process.

3.2 Challenges of using ABM in Construction

As with any method, ABM has limitations or challenges that researchers must face and acknowledge when using this method. During a model formulation, the process in which the system's elements and agents are abstracted may sometimes oversimplify real-life conditions of construction projects. Further, as ABM uses a bottom-up modeling approach, often, the data required to implement the models may not always be available. However, considering that ABM is a fairly new method in CEM, it may be expected to see limited data that fits this specific modeling approach. As such, the implementation of ABM in many areas of CEM may face the challenge of lacking data to initially compare results with, in which case, the role of the validation and verification of agent-based models becomes of paramount importance.

The processes of validation and verification are fundamental on every modeling method, and especially when limited data and information exists regarding a particular modeling approach. Given this context, the verification and validation of agent-based models assumptions and results by subject matter experts (SMEs) are fundamental.

Ultimately, as the implementation of ABM is fairly new in the CEM field, one of the main limitations is the lack of guidelines that can facilitate its implementation (Liang et al., 2016). As such, it is necessary to start discussing different ways and approaches to do so. If we want ABM to be more widely used in the CEM field, it will be necessary to agree on certain common parameters that all researchers can use to compare and verify findings coming from models in this field. Otherwise, it is going to be difficult for researchers to start implementing ABM.

3.3 Recommendations when implementing ABM

This section discusses recommendations about how to move forward regarding the implementation of ABM in the CEM field.

- *ABM is highly recommended as a tool to model problems that require a good understanding of the individual elements of the system under study, such as crew members during a productivity improvement program.*
- *ABM is recommended to be used, especially in problems when the human component of the problem wants to be explored. Examples of making interact ABM with existing technologies in the CEM field, such as BIM, have proven to provide valuable insight into the interaction between facilities' users and BIM designs.*
- *The use of ABM encourages researchers to use or develop theories/principles about the problem under study, which may enrich our understanding of the CEM field. Especially in problems focused on the incorporation of the human component, such as the incorporation of local communities in the management of infrastructure projects.*

- *ABM validation and verification (V&V) processes play a fundamental role as this approach is still under development in the CEM field, and more data and models still need to be collected and developed. As such, subject matter experts (SMEs) should play an active role in the validation and verification of agent-based models.*

4. Conclusions

This study explores the existing literature regarding the use of ABM in the construction engineering and management (CEM) field. Different benefits and limitations identified in the literature are discussed, so to provide recommendations for researchers and practitioners who would like to implement ABM in the future.

This study contributes by discussing existing benefits and limitations of implementing ABM in the CEM field. ABM allows modeling the interaction between multiple individual elements from a system under study, and such interactions lead to emergent behaviors within the system. Consequently, ABM represents a feasible modeling technique to study the inherent complexity of construction projects that allows the study of multiple scenarios spending computing resources instead of actual resources, which can be more cost-effective for CEM practitioners and researchers. Similarly, limitations to ABM were also discussed, such as the requirement of more granular data at the individual level, and the validation and verification processes of models. Ultimately, it was found that if we want ABM to be more widely used in the CEM field, it will be necessary to develop more guidelines and establish clear recommendations to implement ABM, and as such, agreeing on certain common parameters that all researchers can use to compare and verify findings coming from models in the CEM field. Future studies should contribute to the development of more detailed guidelines for the implementation of ABM in the CEM field. For instance, best practices in reporting modeling steps and results would be of great contribution to the CEM field.

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6. References

Ahn, S.; Lee, S. (2015). Methodology for creating empirically supported agent-based simulation with survey data for studying group behavior of construction workers. Journal of Construction Engineering and Management, 141(1).

Al Hattab, M., & Hamzeh, F. (2018). Simulating the dynamics of social agents and information flows in BIM-based design. Automation in Construction, 92, 1-22.

Araya, F.; Faust, K.; Kaminsky, J. (2020). A Decision-Making Framework for Participatory Planning: Providing Water Infrastructure Services to Displaced Persons. Construction Research Congress 2020 Proceedings, Tempe, Arizona, USA, March, 8-10.

ASCE. (2017). 2017 infrastructure report card. Reston, VA: ASCE.

ASCE. (2013). 2017 infrastructure report card. Reston, VA: ASCE.

Bernhardt, K. L.; McNeil, S. (2008). Agent-based modeling: Approach for improving infrastructure management. Journal of Infrastructure Systems, 14(3), 253-261.

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. Proceedings of the National Academy of Sciences 99 (3), 7280–7287.

Cheng, J. C.; Tan, Y.; Song, Y.; Mei, Z.; Gan, V. J.; Wang, X. (2018). Developing an evacuation evaluation model for offshore oil and gas platforms using BIM and agent-based model. Automation in Construction, 89, 214-224.

Echaveguren, T.; Chamorro, A.; De Solminihac, H. (2017). Concepts for modeling road asset management systems using agent-based simulation. Revista Ingeniería de Construcción, 32(1), 47-56.

El-Adaway, I. H.; Kandil, A. A. (2010). Multiagent system for construction dispute resolution (MAS-COR). Journal of Construction Engineering and Management, 136(3), 303-315.

Farshchian, M. M.; Heravi, G. (2018). Probabilistic assessment of cost, time, and revenue in a portfolio of projects using stochastic agent-based simulation. Journal of Construction Engineering and Management, 144(5).

Farshchian, M. M.; Heravi, G.; AbouRizk, S. (2017). Optimizing the owner's scenarios for budget allocation in a portfolio of projects using agent-based simulation. Journal of Construction Engineering and Management, 143(7).

Gan, V. J.; Cheng, J. C. (2015). Formulation and analysis of dynamic supply chain of backfill in construction waste management using agent-based modeling. Advanced Engineering Informatics, 29(4), 878-888.

Grigoryev, I. (2012). AnyLogic 6 in three days: a quick course in simulation modeling. AnyLogic North America.

Hogeweg, P.; Hesper, B. (1983). The ontogeny of the interaction structure in BumbleBee colonies: a MIRROR model. Behavioral Ecology and Sociobiology 12, 271–283.

Hsu, S. C.; Weng, K. W.; Cui, Q.; Rand, W. (2016). Understanding the complexity of project team member selection through agent-based modeling. International Journal of Project Management, 34(1), 82-93.

Jabri, A.; Zayed, T. (2017). Agent-based modeling and simulation of earthmoving operations. Automation in Construction, 81, 210-223.

Lansing, J. S.; Kremer, J. N. (1993). Emergent properties of Balinese water temple networks: coadaptation on a rugged fitness landscape. American Anthropologist, 95(1), 97-114.

Liang, X.; Shen, G. Q.; Bu, S. (2016). Multiagent systems in construction: a ten-year review. Journal of Computing in Civil Engineering, 30(6).

Macal, C.; North, M. (2010). Tutorial on agent-based modelling and simulation. Journal of Simulation 4, 151–162 . https://doi.org/10.1057/jos.2010.3

Micolier, A.; Taillandier, F.; Taillandier, P.; Bos, F. (2019). Li-BIM, an agent-based approach to simulate occupant-building interaction from the Building-Information Modelling. Engineering Applications of Artificial Intelligence, 82, 44-59.

Osman, H. (2012). Agent-based simulation of urban infrastructure asset management activities. Automation in Construction, 28, 45-57.

Porter, S.: Tan, T.; Tan, T.; West, G. (2014). Breaking into BIM: Performing static and dynamic security analysis with the aid of BIM. Automation in Construction, 40, 84-95.

Ren, Z.; Anumba, C. J. (2004). Multi-agent systems in construction–state of the art and prospects. Automation in Construction, 13(3), 421-434.

Ren, Z.; Anumba, C. J.; Ugwu, O. O. (2003). Multiagent system for construction claims negotiation. Journal of Computing in Civil Engineering, 17(3), 180-188.

Shi, J.; Ren, A.; Chen, C. (2009). Agent-based evacuation model of large public buildings under fire conditions. Automation in Construction, 18(3), 338-347.

Taghaddos, H.; AbouRizk, S.; Mohamed, Y.; Hermann, U. (2012). Simulation-based auction protocol for resource scheduling problems. Journal of construction engineering and management, 138(1), 31-42.

Walsh, K.; Sawhney, A.; Bashford, H. (2003). Agent-based Modeling and Simulation in Construction. In Proceedings, Agent-Based Simulation (Vol. 4, pp. 28-30).

Watkins, M.; Mukherjee, A.; Onder, N.; Mattila, K. (2009). Using agent-based modeling to study construction labor productivity as an emergent property of individual and crew interactions. Journal of construction engineering and management, 135(7), 657-667.

Xue, X.; Li, X.; Shen, Q.; Wang, Y. (2005). An agent-based framework for supply chain
coordination in construction. Automation in construction, 14(3), 413-430.

Yang, L.; Mohamed, Y. (2008). Multi-agent resource allocation (MARA) for modeling construction processes. In 2008 Winter Simulation Conference (pp. 2361-2369). IEEE.

Yazdani, S.; Yusof, M. J. M.; Azizi, M. M.; Ali, A. A. A. (2015). An Agent-Based Framework to Improve Coordination in the Process of Urban Infrastructure Provision in Iran. International Journal of Environmental Planning and Management, 1(1), 18-32.

Zhang, P.; Li, N.; Jiang, Z.; Fang, D.; Anumba, C. J. (2019). An agent-based modeling approach for understanding the effect of worker-management interactions on construction workers' safety-related behaviors. Automation in Construction, 97, 29-43.

Zhu, J.; Mostafavi, A. (2017). Performance assessment in complex engineering projects using a system-of-systems framework. IEEE Systems Journal, 12(1), 262-273.