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A REVIEW OF AGENT-BASED MODELING IN CONSTRUCTION MANAGEMENT: AN ANALYTICAL FRAMEWORK BASED ON MULTIPLE OBJECTIVES

Wenyao LIU[1✉], Qingfeng MENG[1], Hanhao ZHI[1], Zhen LI[1], Xin HU[2]

[1] *School of Management, Jiangsu University, 301 Xuefu Road, Zhenjiang 212013, China*
[2] *School of Architecture and Built Environment, Deakin University, 1 Gheringhap Street, Geelong, VIC 3220, Australia*

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Abstract. The increased complexity of construction projects has caused various management challenges. To clarify the mechanism of construction system complexity and improve the ability to manage the complexity of construction projects, the Agent-based modeling (ABM) method has been introduced and used in the construction management field. Nevertheless, a systematic, holistic, and panoramic understanding of the use of the ABM model in the construction management field is still lacking. To address this research gap, this study reviewed 133 historical explorations retrieved from the database of Web of Science. By using the multiple objectives of construction management as the literature classification framework, the study described the research status of the agent-based modeling method in the field of construction management. On this basis, this paper suggested the improvement paths in the application of this method from three aspects. It is expected that this study will provide a theoretical basis for enhancing understanding of the use of the ABM method in construction management, and also provide insights for future explorations in the area.

Keywords: literature review, agent-based modeling, construction management, multiple objectives, bibliometric analysis.

✉Corresponding author. E-mail: *2112210010@stmail.ujs.edu.cn*

1. Introduction

The construction industry is one of the pillar sectors in many parts of the world, and it contributes significantly to the development of national or regional economy (Li et al., 2021a, 2021b). According to the forecast from McKinsey & Company, up to 57 trillion U.S. dollars will be invested in infrastructure construction, especially major projects, around the world by 2030 (Agarwal et al., 2016). Construction management is a type of activity that acquires, allocates, and coordinates construction resources to make projects more orderly and effective (Sheng, 2018). The construction management practices have profound impacts on project performance from different perspectives, such as quality, cost, time, safety, and sustainability. These impacts will also indirectly lead to the engineering industry being affected by different degrees of adverse factors (Huang & Liu, 2021).

However, it is not an easy task to achieve an effective construction management to optimize multiple objectives in engineering construction activities. This is given that engineering construction itself is a relatively complex system, and it faces many challenges resulted from system complexity. The main sources and manifestations of complexity in the engineering construction process are mainly reflected in the following aspects.

First of all, construction and environment (e.g., economic environment, natural environment, social environment) are highly interactive (Zhang et al., 2020a). The environment is dynamic, uncertain, and evolving, and it has close relationships with engineering construction activities (Meng et al., 2021a, 2021b).

Secondly, there are many system elements embedded in engineering construction, and these elements have the features of heterogeneity and adaptability. Specifically, these elements have different attributes and functions. In addition, these elements can actively adjust their state and behavior in respond to the changing environment.

In addition, the overall behaviors and functions of construction projects are complex. These behaviors and functions cannot be achieved merely by individual elements or subsystems, and they are not the simple superposition of the behaviors and functions of individual elements or subsystems. These behaviors and functions are only owned by the system as a whole. For example, multiple objectives in the process of engineering construction are the "emergence" of system behaviors and functions.

These factors bring a variety of challenges to the management of construction projects. To effectively deal with complexity-caused management problems in engineering construction projects and to clarify the system complexity mechanism of such projects, the agent-based modeling (ABM) method is used in the construction management research community. For example, Falcone and Sapienza (2023) use ABM to study the impacts of complex factors such as trust on government in the context of complex international epidemics, The ABM method has unique advantages in dealing with complex problems in a system.

ABM can fully consider the heterogeneity of system elements, interactivity and the adaptability of the subject's behaviors (Knight et al., 2012), and the dynamic evolution characteristics of the environment. In addition, the method can also extract the elements with the interrelated mechanism in the construction system, build a system model from the bottom up, and study the "emergence" at the macro level of the system through the interaction of micro subjects. For instance, Mohan et al. (2023) used ABM to simulate the biased behavior of agents in the development of social interactions. Consequently, it has advantages in analyzing complex, dynamic and nonlinear construction management problems, which is supported by historical studies. For example, Awwad et al. (2017) pointed out that the ABM method is mainly used to analyze the impacts of agent interaction in a system and explain the "emergence" phenomenon at the macro level of such system from the perspective of agent micro behavior interaction. Liang et al. (2018) stated that the ABM method can help to clearly describe the construction process, subjects and complex variables of projects, and it can also solve the dynamic and uncertain problems caused by the constraints of basic factors such as time and space in a construction system. Araya (2020) found that the ABM method can effectively portray agents who can learn independently and produce adaptive behaviors to the changes in projects. Araya (2021) stated that ABM can effectively model the interaction process of relevant elements in the construction of complex system, simulate the entire evolution process of the system, and test the effects of policies and interventions on various scenarios. In addition, the simulation environment of the ABM method is also diverse, especially due to the convenience and benefits brought by the continuous optimization of NetLogo (Carbo et al., 2018).

As complexity is becoming more common in construction projects, complexity has attracted increased attention in the construction management research community. The complexity in the different construction management scenarios involves many system elements, heterogeneous subjects (e.g., owners, designers, supervisors, suppliers, team members), and multiple objectives (e.g., time, cost, quality). Although the ABM method (including the combination of ABM methods and discrete event simulation) is a powerful tool to study the complexity of construction management (Monks et al., 2019; Xu et al., 2022), a holistic understanding of its application in the construction management area is still lacking. Due to the lack of such holistic understanding, it is difficult to put forward prospects for its future development and research trends.

It is well known that engineering management has multiple objectives, such as profit, quality, cost, schedule, technological innovation, environmental protection, industry competition, and maintenance of cooperative relationships. The achievement of each objective will, to a certain extent, be related to the complete success of the project itself. In order to achieve or optimize the objectives, scholars have adopted multi-subject modeling methods to carry out relevant research for a specific problem in engineering management. Therefore, the study aims to address this research gap by comprehensively and systematically reviewing literature using the ABM method in construction management. The study will also set up a reasonable classification framework to classify them according to the multiple objectives emphasized in the engineering construction projects. On this basis, this study depicts a comprehensive picture of the research status of using the ABM method in construction management. The scientific atlas software CiteSpace was used in this study to analyze the relevant literature, understand research hotspots and current status, and suggest future research directions.

Compared with some existing reviews of ABM in the field of engineering management (such as *Agent-based modeling and simulation in construction*), this paper is characterized by: (1) adopting a multi-objective classification framework, (2) more inclined to the perspective of construction management, which focuses on reviewing the relevant literature of using this method to study the behavior of the subject, rather than biasing the review of engineering technology optimization and simulation with ABM in construction management, (3) focusing on the application dimension of the ABM method, and (4) using different criteria to screen core literature.

The study has several innovations. First of all, there are limited explorations on the application of ABM in engineering, this article tries to collect more comprehensive literature. Compared with the previous literature on the engineering technology (such as *Agent-based modeling and simulation in construction*), this article focuses more on the ABM application in the construction subject behavior modeling and simulation research, which demonstrates the use of this method in the field of construction management. Additionally, this paper tries to seek a new and more reasonable classification framework. Based on the analysis indicators of bibliometrics, the targets are classified from multiple angles. Therefore, researchers can more conveniently clarify the research status and trends in this field. In addition to some traditional targets, some of the new goals of project management are discussed in this paper, such as risk, sustainability, and coordination. Furthermore, compared with the previous research (such as the study "*Applications of multi-agent systems from the perspective of construction management: A literature review*"), this article systematically combed the defects of using the ABM method, proposed the directions to improve, and helped practitioners or researchers to make the application of ABM more scientific and effective in the field of project management.

The structure of this paper is organized as follows. First, the literature collection and selection methods in the Web of Science database are described. And then, the corresponding scientific mapping analysis of the literature was performed by using the bibliometric software CiteSpace and the keywords co-occurrence and keywords burst detection maps were derived. After that, a comprehensive review of the current research status of ABM in construction management is provided from the perspective of multiple construction management objectives. On this basis, the advantages and deficiencies of using ABM in the construction management research were discussed and future research development trends were also suggested. All these provide a valuable reference for the theoretical and practical development of this field.

2. Research methods and material preparation

2.1. Literature search and selection

The Web of Science (WOS) database was used for literature searching. WOS has powerful analysis abilities, which can quickly locate high-impact papers and identify research directions concerned by global researchers, especially by using the Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) in the core collection of WOS. These two academic journal citation index databases contain the most comprehensive list of high-impact academic journals in the world, which is leading and instructive (Liu et al., 2021). In addition, WOS has been confirmed as the most convenient database used for the bibliometric analysis of documents (AlRyalat et al., 2019). Many scholars have chosen the WOS database for their literature reviews (Li et al., 2022; Liang et al., 2020; Olawumi et al., 2017; Wang et al., 2023; Zhang et al., 2020a; Zhao, 2017; Zhong et al., 2019). The search was limited to the years 2001–2023 and was conducted on 8/1/2023. Table 1 shows the keywords used in searching.

This paper used the PRISMA four-stage flow chart to screen the documents in the search results (Moher et al., 2009). The specific screening process and results are shown in Figure 1. First, a literature search was conducted separately based on topics A and B, but it was found that the amount of literature contained in both was huge. Therefore, the topics A and B were integrated, and a topic C was established. A total of 453 literatures were obtained through searching the topic C.

On the basis, the manual screening was performed. Some studies published in non-construction fields (e.g., transportation, biology, and computer science) were excluded. Therefore, 148 studies were identified. After discarding the literature in the review category and some editorial materials, 133 literatures were finally used for the subsequent analysis.

2.2. Literature analysis based on statistical and bibliometric tools

2.2.1. Preliminary statistical analysis

Firstly, the publication trends in different years were analyzed (Figure 2). As shown in Figure 2, fewer papers were published in this area before 2013. However, the interest in this direction increased after 2013. In particular, the number of papers published in the field increased significantly during 2015–2023, with the highest number of papers being published in 2022. This trend suggests that the increased interest in using the ABM method in the field of construction management, which was promoted by various factors, such as the continuous development of computer technology and the current development concept of cross-fertilization between disciplines.

Additionally, it was found that the selected 133 papers were sourced from 44 journals (Table 2). The highest number of papers (28) were published in the journal *Automation in Construction*, accounting for 21% of the all the published articles. This is followed by the *Journal of Construction Engineering and Management* and *Journal of Computing in Civil Engineering*, with a publication volume of more than 10 articles. The number of articles published in other journals is only between 1 and 5 articles. It was also found that about 70% of articles are published in journals related to construction engineering.

Table 1. The keywords used in searching on Web of Science and the search results

Topic	Keywords	Web of science
A	(Agent-based modeling) OR (Agent-based simulation) OR (Agent-based modeling and simulation) OR (Agent-based model) OR (Multiagent-based simulation) OR (Multiagent simulation)	5009
B	(Construction) OR (Construction management) OR (Construction project) OR (Building) OR (Engineering)	42698
C	A AND B	453

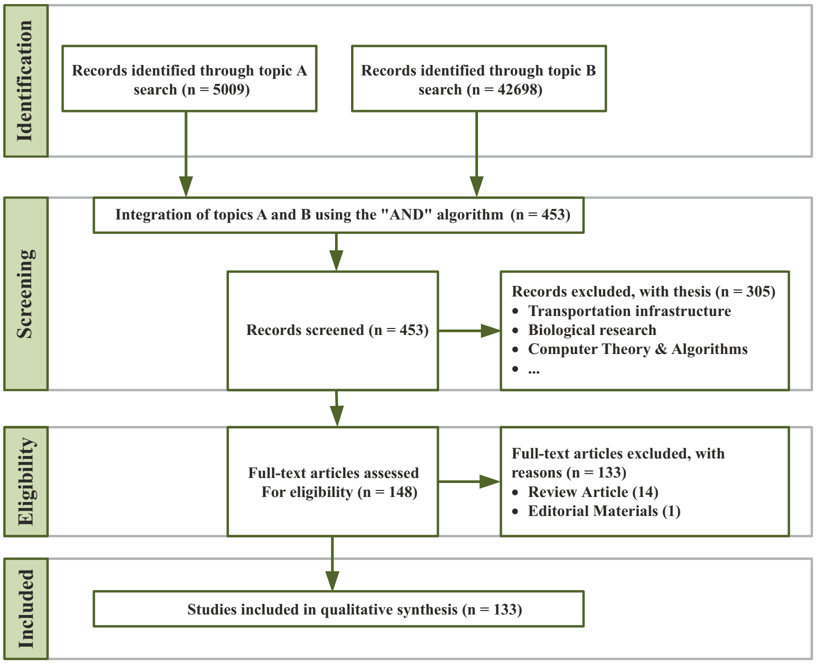

Figure 1. Flowchart of systematic review process (PRISMA flow diagram)

Table 2. Review sources of 44 academic journals during 2002 to 2023

Journals	No.	Journals	No.
Automation in Construction	28	*Applied Artificial Intelligence*	1
Journal of Construction Engineering and Management	17	*Bauingenieur*	1
Journal of Computing in Civil Engineering	12	*Canadian Journal of Civil Engineering*	1
Journal of Management in Engineering	5	*Civil Engineering and Environmental Systems*	1
Engineering, Construction and Architectural Management	5	*Computational Intelligence and Neuroscience*	1
Journal of Cleaner Production	5	*Energy*	1
Safety Science	4	*Energy and Buildings*	1
Buildings	4	*Environment, Development and Sustainability*	1
Sustainability	4	*Environmental Science and Pollution Research*	1
Complexity	3	*European Journal of Environmental and Civil Engineering*	1
Jasss-the Journal of Artificial Societies and Social Simulation	3	*Environment and Planning B-Urban Analytics and City Science*	1
Journal of Building Engineering	3	*Humanities & Social Sciences Communications*	1
Accident Analysis and Prevention	2	*Healthcare*	1
Advanced Engineering Informatics	2	*Periodica Polytechnica-Civil Engineering*	1
Expert Systems with Applications	2	*Plos One*	1
International Journal of Environmental Research and Public Health	2	*International Journal of Occupational Safety and Ergonomics*	1
International Journal of Project Management	2	*Revista De La Construccion*	1
Journal of Civil Engineering and Management	2	*Scientia Iranica*	1
Journal of Simulation	2	*Iranian Journal of Science and Technology-Transactions of Civil Engineering*	1
Waste Management	2	*Sustainable Cities and Society*	1
Ain Shams Engineering Journal	1	*Science of the Total Environment*	1
Alexandria Engineering Journal	1	*Tehnicki Vjesnik-Technical Gazette*	1
Total			133

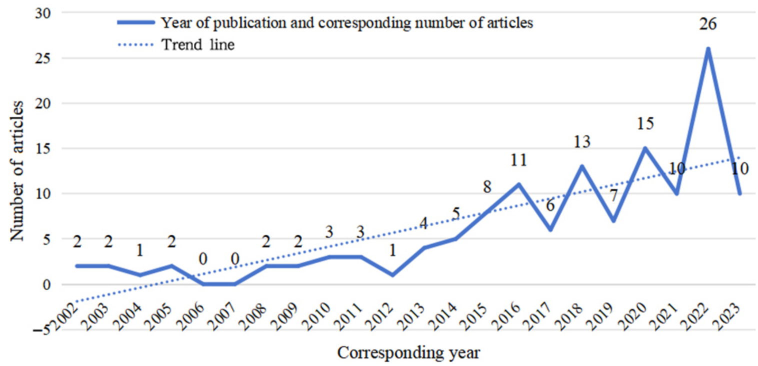

Figure 2. The number of publications in different years (2002–2023)

2.2.2. Analysis of keywords and hot topics distribution

CiteSpace is a bibliometric visualization software based on the Java language. It is widely used in various fields because it can visually display various contents contained in documents through scientific graphs, and enable researchers to quickly understand the current status and evolution direction of research fields (Chen et al., 2020; Geng et al., 2022).

Using CiteSpace software to analyze keywords (such as keyword co-occurrence, keyword clustering, timeline and keyword citation explosion) can help reflect the current status, hotspots, and evolutionary directions of the studied research field (Meng et al., 2020; Qiu et al., 2022).

Figure 3 shows an overview of the keyword co-occurrence network generated by using CiteSpace to extract core data. It can be seen that "agent-based modeling" and "performance" are the keywords with the highest frequency of occurrence. This is followed by simulation, model, management, climate, construction, and systems. This result confirms the research themes of this study. As the main research method, the keyword "Agent based modeling" appears in almost every article. The ultimate goal of using the ABM method for research in the construction field is almost always to improve the performance of a certain aspect of the project. Therefore, the frequency of "performance" is also high. In addition, other frequently occurring keywords highlight the overall directions of the research, which is named as the "Application of ABM method in the construction field".

Based on the keyword co-occurrence network analysis, the timeline map (Figure 4) produced by CiteSpace software shows the emergent analysis of keywords in the literature. Through this presentation method, it was found that researchers have a clearer understanding of the changes in research hotspots in the field over time and the clustering of keywords (Zang et al., 2022).

The main steps were shown as follows: (1) 133 documents from the WOS database were saved in the text format in CiteSpace. (2) The relevant parameters of the software were set (Lin et al., 2022). For example, the time interval was set from 2002 to 2023, and the time slice was set to 1 year. The nodes analyzed mainly included keywords (title, abstract, and keywords). The g-index in selection citation was set to 25. (3) Running CiteSpace yielded Nodes = 236 and Links = 1032. The study obtained Q = 0.5859 (>0.5) and S = 0.8678 (>0.7) by using the LLR algorithm and keywords (K) for clustering and naming of clustering labels, indicating very good clustering and convincing clustering results (Chen, 2017). To better visualize the research hotspots under temporal changes, the corresponding timeline functional modules were used to obtain Figure 4 (timeline map showing the research temporal evolution trends and relationships of ABM methods in engineering after keyword clustering) (Dang et al., 2021). (4) On the basis of the mapping, the current research status of ABM methods in the engineering field was analyzed, and this analysis helps to determinate the classification framework below.

Figure 4 shows that the keywords in the literature are clustered into 8 categories. The left side of the category is the change and connection between the keywords contained in each category. The circle represents the first appearance of the keywords, the line represents the connection between the keywords under time change, and the size of the circle is positively related to the frequency of the keywords (Sabe et al., 2022).

By analyzing the clusters, eight clusters from three levels were identified. First, clusters #0 and #3 represent the "IT" and "construction" industries, which indicates that the current research involves the intersection of disciplines. Second, cluster #5 is "agent-based modeling", which represents the mainstream methodology of current research. Finally, clusters #1, #2, #4, #6 and #7 seem to favor some research themes. Cluster #1 is "cooperation", and it was noticed that its keywords are "communication", "congruence", "conflict", and "dispute resolution". Given that the completion of a construction project involves the negotiation and cooperation of multiple parties inside and outside the organization, this cluster is named as "cooperation". Cluster #2 is "safety behavior", which indicates that the ABM method is widely used in construction safety. Cluster #4 is "emergent construction", the related data were checked and found that there is no precise definition of this term. Combining some key words, such as "project flow", "system", "contractor selection", "key factor", it was found that this category focuses on the system flow and

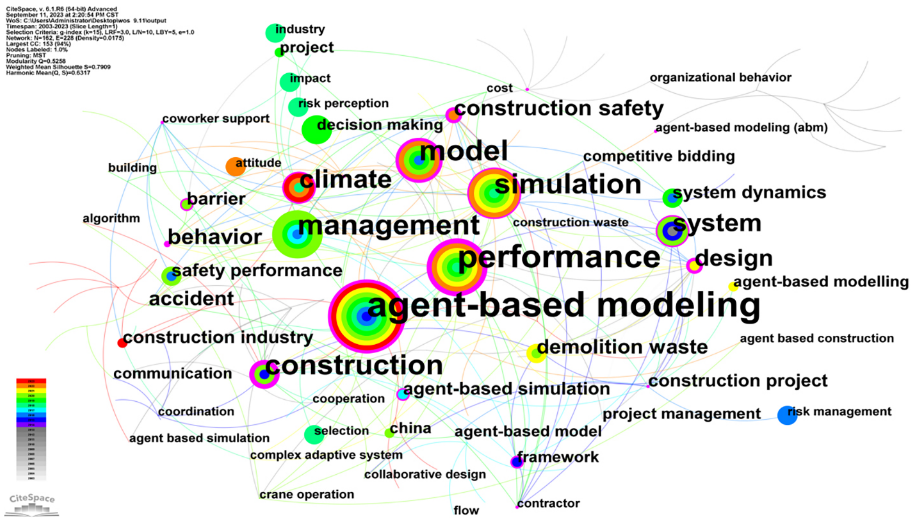

Figure 3. Keywords co-occurrence network of ABM in construction field research

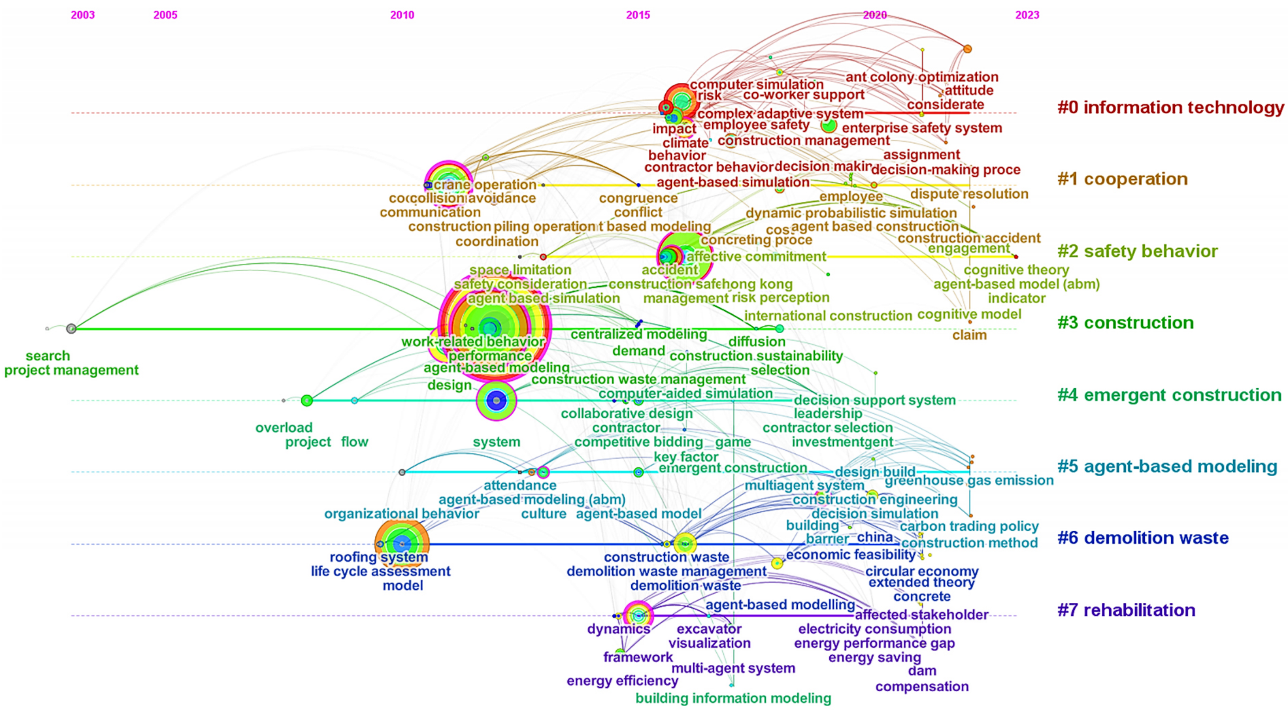

Figure 4. The clustering results in LLR algorithm (Timeline map)

the selection of factors. Combined with the meaning of the word "emergency", it was speculated that the main orientation of this cluster is "fast project completion". Cluster #6 focuses on the disposal of building waste, and cluster #7 focuses on the efficiency and renewability of building energy. Both clusters #6 and #7 emphasize the concept of green and sustainable development in the construction industry. The cluster analysis for keywords also helps in subsequent multi-objective based topic categorization and content analysis.

2.2.3. Burst words analysis

Keyword prominence is the detection of keywords that increase over time to reveal the hot research topics in that period and predict which hot keywords will continue the explosive trend in the future and become the research hotspots in that research area. By setting the Burstness function in Citespace to 0.2 and the Minimum Duration to 2, 25 emergent keywords with high burst intensity for the current state of research on ABM methods in construction management from 2002–2023 were identified (see Figure 5).

Figure 5 shows the research hotspots of ABM in the field of engineering evolve over time from 2002–2023. The first word to appear was "project management", which appeared in 2003 and lasted for 10 years from 2003 to 2012. This indicates that the earliest research in the field centered around construction project management. The second hotspot that lasted longer was the "life cycle assessment", which lasted for 7 years. This reflects the application of the ABM methodology throughout the entire

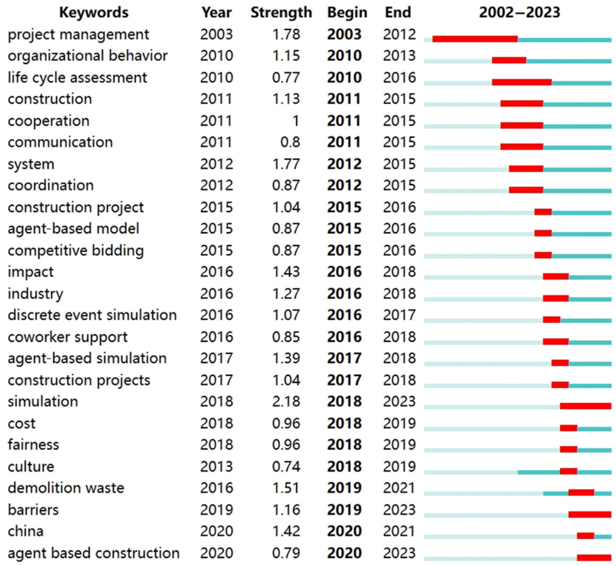

Figure 5. Top 25 Keywords with the Strongest Citation Bursts

life cycle of a construction project. It also shows that with the rapid development of global economy and technology, the complexity of engineering (especially the complexity of management) has increased dramatically, and all aspects of engineering project management have received the attention of researchers and have been explored using the ABM methodology (Tho et al., 2017). Many of the keywords included in this time period (e.g., organizational behavior, cooperation, communication, coordination) corroborate the complexity of construction projects. In recent years, the hotspot of longer duration is "obstacles" (lasting for 5 years). This continues to demonstrate the unique strengths of the ABM approach in dealing with disturbances and obstacles in the complex construction projects. In addition, "demolition waste" has also been a hot topic in recent years. This shows that green and sustainable development has become the focus of relevant researchers (Meng et al., 2021a), and therefore, corresponding studies have gradually emerged.

3. Content-based literature review

Through content analysis of the selected literature, it is found that categorizing the papers according to the multi-objectives of engineering management helps to highlight the research objectives and themes of each paper. The multi-objective framework contains multiple aspects of objectives, closely follows the actual development of engineering, and constantly incorporates new objectives. Finally, based on the existing objectives of engineering management, the current status of the application of the ABM method in engineering were summarized and analyzed. It was found that there is a gradual move towards a high level of engineering management to achieve high efficiency in engineering construction through constantly overcoming the challenges of the complexity of many systems. In this study, by analyzing the research contents of 133 literatures, it was found that the construction management-based multi-objective classification method can highlight the research objectives and themes of each literature, and make the classification of the literature clearer. In the analysis process, the content-based analysis method was adopted. First, on the basis of bibliometric analysis, further manual intensive reading of the literature was carried out to sort out and understand the complex background, specific content and main research objectives of the 133 literature sources. On the basis, the study combined the current status and trend of the development of the ABM method in the field of construction management, grasped the 133 literature sources comprehensively as a whole, and finally reasonably categorized them from the perspective of multi-objective. The selected historical studies can be categorized according to different construction management objectives (Table 3). Table 3 shows that most of the historical studies were examined in terms of four objectives, namely: "safety performance improvement", "duration optimization", "sustainable development", and "coordination of multi-party relationships". In addition, the research objectives of "cost saving", "quality control" and "risk management" are further identified.

Table 3. Literature classification based on multiple objectives

Classification of research objectives	Number (percentage)
Safety performance improvement	41 (31%)
Duration optimization	23 (17%)
Cost saving	5 (4%)
Quality control	8 (6%)
Risk management	8 (6%)
Sustainable development	21 (16%)
Coordination of multi-party relationships	24 (18%)

3.1. Safety performance improvement

Using ABM as the main research methodology, the first type of research focuses on the safety performance improvement. Table 4 lists the main dimensions of the current study, the sub-objectives of each dimension, and the representative literature.

Safety behavior of construction workers is identified as one of the most important factors in improving safety performance in construction sites (Li et al., 2021a; Meng et al., 2021b). As a result, a large number of studies have focused on the improvement of worker safety behavior. For example, Goh and Ali (2016) proposed a hybrid framework by combining agent-based model (ABM), system dynamics (SD), and discrete event simulation (DES), and demonstrated the feasibility of the framework through sensitivity analysis and factorial experiments in hypothetical earthwork cases. Managers can use this hybrid framework to evaluate the impacts of complex decisions on workers' safety behavior. Wehbe et al. (2016) simulated the elasticity of social networks in construction through NetLogo, analyzed how the interaction involving safety behavior affects safety performance and anti-risk capability and concluded that anti-risk elasticity and safety performance is positively affected by interaction and network structure. Choi and Lee (2018) analyzed how safety behavior under different risk conditions changes under the interaction of social cognitive processes and safety intervention measures under the cognitive process theory, and concluded that the degree and frequency of management feedback and project identification can improve construction safety. Li et al. (2018) constructed a three-tier structure model, analyzed the complex mechanism of unsafe behavior of construction workers, and studied the impacts of workers' unsafe behavior under several incentive strategies and management scenarios. Liang et al. (2018) studied how safety violations are affected by different management measures under the interaction of workers and the environment. And the study found that different safety management measures are applicable to different levels of danger. Based on the risk theory, Ji et al. (2019) simulated the accidental injuries that workers may suffer at construction sites to analyze the impacts of two types of colleague support behavior on safety performance. Zhang et al. (2019) analyzed the effects of different management factors on safety performance in four management scenarios through simulations, and quantitatively examined these factors (including the responsibilities and capabilities of managers, etc.). It is concluded that the ABM method can effectively evaluate the influencing factors of workers' safety-related behavior. Liang and Lin (2019) used hybrid system dynamics (SD) and agent-based modeling (ABM) to simulate the main decision-making rules and interactive behaviors in construction projects and analyzed the social contagion mechanism of workers' violations and the impacts of the interaction of environmental factors on safety strategies. Ye et al. (2020) analyzed the social cognition process of workers in the interaction with managers and colleagues during construction and showed the reasons for the failure of workers' cognition and the roles of social factors. Lu et al. (2016) deployed ABM to explore how various safety investments could influence safety behaviors, as well as the interactions of individuals on a micro level, and the subsequent safety performance of an entire project. He et al. (2023) systematically explored the influence of multiple (individual, organizational, etc.) factors of the decision-making process of workers' safety behavior on the dynamic safety performance. The results indicate that workers' psychological decision-making processes are the result of multiple factors.

A construction site is a dynamic and complex system, and many specific operations (e.g., lifting, material transportation, working at heights) require the use of equipment to complete (Zhang et al., 2020b). However, as unsafe conditions of equipment can lead to serious safety accidents, monitoring and evaluating equipment conditions are needed (Liu et al., 2021). Lee and Bernold (2008) developed an AB wireless communication system for severe weather construction sites, where hazardous wind conditions are predicted from sensing data and warnings are sent to crane operators via an alerting agent, enabling them to make autonomous decisions about the crane operation plan. Zhang and Hammad (2012) determined the priority of crane equipment and planned the movement path of equipment in real-time by studying the negotiation and communication of site status agents, coordinating agents, and crane agents to avoid collision accidents. Vandatikhaki et al. (2017) created an architecture that combines the Location-based Guidance Systems (LGS) technology with security management knowledge, proposed a security mechanism that can achieve two types of responses, and demonstrated that the system can improve the coordination between construction equipment and prevent collision accidents through a case study. In addition, Lu et al. (2020) analyzed the main influencing factors of the imbalance between shield machines, humans and the environment, and safety performance in tunnel construction by developing an agent-based safety system. This system can identify risk factors, and the effectiveness of the system was also verified. Liu et al. (2020b) used the ABM method and structural entropy to calculate the safety evaluation index weights of the steel structure at-

Table 4. Classification of studies on safety performance improvement

Objective	Main dimensions and codes	Sub-objective	Representative literature
Safety performance improvement	(1) Worker safety behavior	Exploring the interaction between safety related influencing factors and their impact on safety behavior	Goh and Ali (2016), Wehbe et al. (2016), Choi and Lee (2018), Li et al. (2018), Liang et al. (2018), Ji et al. (2019), Zhang et al. (2019), Liang and Lin (2019), Ye et al. (2020), Lu et al. (2016), He et al. (2023)
	(2) Equipment safety	Real-time tracking and monitoring of large construction equipment to avoid accidents as much as possible	Lee and Bernold (2008), Zhang and Hammad (2012), Vandatikhaki et al. (2017), Lu et al. (2020), Liu et al. (2020b)
	(3) Safety evacuation	Enhanced building layout design through ABM helps to improve the efficiency of safety evacuation in case of sudden emergencies	Mirahadi et al. (2019), Ha and Lykotrafitis (2012), Arteaga and Park (2020), Zhou et al. (2020), Manley and Kim (2012), Naili et al. (2019), Li and Xu (2020)
	(4) A few other interesting perspectives	Exploring the impact of a factor on safety performance from a more alternative perspective	Araya (2021)

tached lifting scaffold and used the grey relative Euclidean weighted correlation theory to establish a safety evaluation model.

In the event of an emergency, evacuation of the crowd is required to safeguard the lives of the people. Reasonable building design and layout can help the crowd to evacuate efficiently (Mirahadi et al., 2019). This is also a reflection of high-quality safety performance. Most studies focus on the design variables in buildings (e.g., geometric properties of doors, exits, rooms, corridors, stairs). Ha and Lykotrafitis (2012) aimed to optimize the size of doors and exits in complex multi-room multistory buildings. Arteaga and Park (2020) focused on optimizing the exit widths, door widths, and corridor widths of buildings during indoor shootings. Zhou et al. (2020) worked on improving the design of staircases. Manley and Kim (2012), Naili et al. (2019), and Li and Xu (2020) applied ABM to enhance the design of building layouts or building components, and explored the optimal design of exits, door operability, and shelf locations through taking into account different pedestrian characteristics (with special attention to the elderly, children, and the disabled).

There are some alternative studies in the studied area. For instance, Araya (2021) simulated the spread of COVID-19 among construction workers in different risk activities and analyzed the impacts on worker safety and construction project performance. Meanwhile, the adoption of multi-shift management measures can minimize the degree of industrial worker density, which reduces the spread of COVID-19 and improves the safety performance of projects.

3.2. Duration optimization

The ABM method was also used to study the construction duration optimization issues. Table 5 lists the main dimensions of the current study, the sub-objectives of each dimension, and the representative literature.

It was found that a large number of articles on duration optimization focus on productivity improvement. Firstly, the relevant research on the impact of human oriented labor productivity improvement on duration optimization was analyzed. For example, Watkins et al. (2009) analyzed the impacts of the interaction between individual workers at construction sites on labor productivity and spatial congestion. The study results indicate that congestion can be used as a sudden feature and temporal and spatial dynamics, and the increase in efficiency may lead to the loss of time and space in the construction process. Du and El-Gafy (2012) analyzed the collective behavior generated by the interaction between employee behavior and organization and its impacts on the project construction schedule by establishing the virtual organizational integration for construction enterprises model. The study found that voice is an effective method to understand interactions. Ahn et al. (2013) analyzed the mechanism of workers' social learning and the relationships and roles of absenteeism, social norms, and labor control. The findings of this study showed that the cultivation of social norms can improve attendance and project productivity. Du and El-Gafy (2015) analyzed the mechanism and impact of the differences in the behavioral cognition and management standards of stakeholders in project development and showed that a comprehensive and systematic investigation of behavior is necessary to improve project efficiency. Kiomjian et al. (2020) analyzed the influence mechanism of worker interaction on social learning based on different personnel compositions and project schedules and concluded that team diversification is positively related to the level of knowledge sharing and productivity.

Improvements in equipment efficiency also helped the project progress. Marzouk and Ali (2013) proposed a productivity estimation model to study the impacts of safety and space availability on the productivity of piling equipment at construction sites to improve the project schedule. Matejevic et al. (2018) used the AnyLogic software to establish a productivity prediction model based on discrete events and agent-based modeling. The study analyzed the constraints affecting concrete production capacity at construction sites to accurately plan the concrete production process and shorten the construction duration. Naticchia et al. (2019) integrated ABM and BIM to develop a generic

Table 5. Classification of studies on duration optimization

Objective	Main dimensions and codes	Sub-objective	Representative literature
Duration optimization	(1) Productivity (manpower-oriented)	Exploring the impact of labor productivity on project schedule acceleration	Watkins et al. (2009), Du and El-Gafy (2012, 2015), Ahn et al. (2013), Kiomjian et al. (2020)
	(2) Productivity (equipment-oriented)	Evaluate and improve equipment performance to increase efficiency	Marzouk and Ali (2013), Matejevic et al. (2018), Naticchia et al. (2019), Khodabandelu et al. (2020)
	(3) Supply chain information sharing	Accurately control the quantity, quality and cost of the required materials and deliver them to the construction site in a timely manner	Obonyo et al. (2005), Tah (2005), Min and Bjomsson (2008), Jung et al. (2018)
	(4) Other influencing factors	A number of other factors (e.g., negotiations, choice of delivery system, etc.) can also have an impact on the project duration	Meng et al. (2019); Zhu et al. (2020)

online platform for efficiently managing the execution of bored piles. Khodabandelu et al. (2020) developed an AB model to explore the most efficient allocation of material supply locations and cranes to each task on a large multi-crane site by considering all potential collisions.

Getting the right quantity, quality, and cost of materials to the construction site in a timely manner is important for the completion of projects on schedule. The incomplete data availability due to dispersed information or lack of proper communication hinders proper decision-making at every stage of the supply chain and slows down duration. Therefore, timely sharing of supply chain information is also critical for duration optimization. For example, Obonyo et al. (2005) centralizes information through an online platform. Tah (2005) built a multiagent prototype system to pre-plan a collaborative project supply network for more efficient business processes. Min and Bjomsson (2008) developed the construction industry supply chain simulator (CS2), analyzed the value of real-time information sharing in the construction industry, and found that real-time information sharing can effectively reduce the construction time of a project and improve the performance of the construction supply chain. Jung et al. (2018) proposed a model combining discrete event simulations and ABM to simulate and analyze the relationships and influence mechanisms between construction, material supply, and resource sharing, and verified that the model is effective in improving the progress of projects.

Some other scholars have studied the duration optimization from other perspectives. For example, Meng et al. (2019) discussed the influence of competitive preferences and social welfare preferences on the negotiation between contractors and owners for the optimization of construction project schedules. The study found that greed will lead to longer negotiation time and lower success rate, and social welfare preferences do not affect the revenue sharing coefficient and negotiation time. Zhu et al. (2020) comprehensively analyzed the influence mechanism of decisive factors such as project characteristics and environment on the project delivery system (PDS) decision and concluded that the choice of PDS will directly affect the project construction duration.

3.3. Cost saving

Using ABM as the main research methodology, the third type of research focuses on cost savings. Table 6 lists the main dimensions of the current study, the sub-objectives of each dimension, and the representative literature.

Labor costs are firstly considered as people are the most important subjects in a construction project. For example, Dabirian et al. (2016) studied the influencing factors of labor costs in complex project processes and concluded that multi-agent simulation can more accurately predict changes in labor costs compared with planned costs in construction projects.

Effective maintenance and repair can go a long way in avoiding facility system failures and reducing the corresponding financial losses (Trappey et al., 2013). To address this issue, related research has used ABM and combined it with other tools to develop a maintenance and repair framework. For example, Shen et al. (2012) developed an AB platform that integrates BIM and the sensing technology, which can capture relevant data from all facility lifecycle stages and provide optimal decision support for facility management and maintenance. By using the game theory, Trappey et al. (2013) combined ABM with the sensing technology to develop a collaborative maintenance decision support platform.

Researchers have also focused on the impact of project portfolios on project costs. Farshchian et al. (2017) took the increased cost during construction and the increased income after completion into account in the model, simulated and analyzed how the four optimization schemes and the budget cost in the portfolio affect the project progress. The study concluded that the maximum productivity optimization scheme has the best comprehensive effect compared with the three schemes such as the lowest residual cost. On this basis, Farshchian and Heravi (2018) simulated and analyzed the progress, time, and cost of the project portfolio in different scenarios, and verified that the model can effectively improve the organization's revenue cost forecast and reduce its risk level.

3.4. Quality control

Using ABM as the main research methodology, the fourth type of research focuses on quality control. Table 7 lists the main dimensions of the current study, the sub-objectives of each dimension, and the representative literature.

In addition to focusing on the production progress of the project, attention should also be paid to the completion quality of the project. There is relatively little literature focusing on this issue, and researchers mainly conducted research from two perspectives, including bidding methods and the attributes of workers.

Table 6. Classification of studies on cost saving

Objective	Main dimensions and codes	Sub-objective	Representative literature
Cost saving	(1) Labor cost	Using ABM to accurately forecast labor costs helps projects spend wisely	Dabirian et al. (2016)
	(2) Maintenance and repair of facilities	Effective maintenance of facility systems can reduce economic losses	Shen et al. (2012), Trappey et al. (2013)
	(3) Project portfolio	Help organizations optimize budget al.ocation scenarios to reduce construction costs	Farshchian et al. (2017), Farshchian and Heravi (2018)

Table 7. Classification of studies on quality control

Objective	Main dimensions and codes	Sub-objective	Representative literature
Quality control	(1) Bidding methods	Proper bidding contributes to the overall quality assurance of the project	Awwad and Ammoury (2019)
	(2) Attributes of workers	Differences in the behavior of workers with different attributes can affect some quality aspects	Ben-Alon and Sacks (2017), Wu et al. (2019)

Awwad and Ammoury (2019) focused on the issue that the choice of bidding method may affect project quality. Awarding the project to the lowest bidder could lead to hostile relations, reduce cooperation between the project parties and potentially affect the quality of projects. From the perspective of the owner, the authors simulated and analyzed the dynamic evolution of the price and the market during the bidding process and how to choose the best competitive bidding method under restrictive conditions. Simulation results showed that the below-average bid method is most favored for less-competitive projects, whereas the second low bid and average-bid methods are preferred when the level of competition is high.

Differences in the behavior of workers with different attributes can also have an impact on some quality aspects. Ben-Alon and Sacks (2017) incorporated decision-making, behavior, and perception in construction into the model, simulated through similar scenes to verify the model, and concluded that the multi-agent behavior model can effectively control production and quality issues in building construction. Wu et al. (2019) analyzed the impacts of different attributes and behavior differences of employing multiple types of workers on project performance and concluded that the behavior of employed workers is affected by surrounding environmental factors (e.g., engineers, external environment). Insufficient estimation of production quality and absence rate caused by behavior differences will lead to serious deviation of projects.

3.5. Risk management

Using ABM as the main research methodology, the fifth type of research focuses on risk management. Table 8 lists the main dimensions of the current study, the sub-objectives of each dimension, and the representative literature.

In the field of risk research in construction management, one type of study considered whether a number of uncertainties could potentially affect the feasibility of the project. Jo et al. (2015) combined ABM with SD to build a project feasibility analysis platform. Mostafavi et al. (2016) applied ABM to simulate and study potential financing strategies for road construction projects at the feasibility study stage. Raoufi and Fayek (2018) developed a multi-agent model (FABM) based on the fuzzy logic for the problem of uncertainty affecting construction quality, analyzed the interaction and subjective uncertainty between construction personnel in the construction system, and verified that the model can effectively improve the performance appraisal and deal with the subjective uncertainty in projects. Korb and Sacks (2021) utilized ABM to examine how applying a different, new, and creative paradigm to the relationships between general contractors and subcontractors affects the final outcome of a project.

Risks are complex as they may interact or change throughout project implementation. Therefore, it is important to identify and assess the potential risks of a project (Taillandier et al., 2015). Karakas et al. (2013) developed an AB model that is able to allocate risks and associated cost overruns due to risks among the stakeholders of a construction project in any possible scenario. Taillandier et al. (2015) studied the complexity caused by the interaction and changes between risks in the process of construction projects, evaluated the impacts of risks on projects and stakeholders through the model, and confirmed that the model can effectively test risk mitigation strategies. On this basis, Taillandier et al. (2016) considered that the previous stochastic multi-agent simulation model was rigid and could not well describe the process and modeling. Therefore, a new smacc2 model was developed to better mitigate the risk of complex construction projects. Asgari et al. (2016) simulated the market bidding process under different combinations of risk attitude and pricing behavior, and analyzed that the contractor's performance is affected by different combinations of work needs and risk allowances based on fixed pricing under three market environments. It is concluded that moderate risk attitude and work needs are the most effective strategies, and extreme lack of risk aversion and work needs are the most ineffective decision taken by contractors. Du et al. (2020) proposed an evaluation model for the effect of design change management to study the risk coordination mechanism of

Table 8. Classification of studies on risk management

Objective	Main dimensions and codes	Sub-objective	Representative literature
Risk management	(1) Feasibility analysis	Assess some of the uncertainties and explore their impact on the success of the project	Jo et al. (2015), Mostafavi et al. (2016), Raoufi and Fayek (2018), Korb and Sacks (2021)
	(2) Identification of risk factors	Identify potential risks and utilize the AB model to mitigate the negative impact of risk interactions on project success	Karakas et al. (2013), Taillandier et al. (2015, 2016), Asgari et al. (2016), Du et al. (2020)

design change, and to improve project performance and reduce the risks caused by design changes.

3.6. Sustainable development

Using ABM as the main research methodology, the sixth type of research focuses on sustainable development. Table 9 lists the main dimensions of the current study, the sub-objectives of each dimension, and the representative literature.

Effective management of construction waste contributes to environmental sustainability (Liu et al., 2020a; Ogunmakinde et al., 2022; Wu et al., 2017). Many researchers have applied ABM to explore this issue. For example, Gan and Cheng (2015) compared the performance of centralized optimization and distributed agent optimization models in the context of a complex backfill supply chain, and concluded that agent-based models are more suitable for complex research in the backfill process. Ding et al. (2016) proposed an environmental impact assessment model to study how environmental performance changes under the influence of attitudes and the interaction of various stakeholders. The findings indicated that deconstruction methods and oriented design have significant impacts on demolition waste management. Ding et al. (2020) studied the environmental effects of the policies generated by the interaction of stakeholders in the management of waste renovation and concluded that reducing the sources of renovation waste is the most effective strategy. Ding et al. (2021) simulated and quantified the changes in the data warehouse during the waste treatment process in Shenzhen, China, and concluded that the deconstruction method is more effective in reducing construction waste. Stakeholders and demolition companies should pay more attention to the improvement of demolition waste management. Yu et al. (2021) focused on the sustainability of reusing concrete waste. By combining geographic information system (GIS) and ABM methods, the authors studied the dynamic collaboration of stakeholders in the waste supply chain, and the findings showed that recycled concrete aggregate information system exists implicitly.

Some studies focus on energy management issues in the construction industry (especially reducing energy consumption). Liang et al. (2019) evaluated the effectiveness of various government energy efficiency incentive strategies in reducing energy consumption and found that governments can incentivize homeowners by paying special attention to energy prices. Rosales-Carreon and Garcia-Diaz (2015) collected stakeholders' views on near-zero energy buildings based on innovative theories and qualitative methods and analyzed the impacts of knowledge owned and shared by participants on preventing excessive near-zero energy buildings. Ali et al. (2020) simulated and analyzed the impacts of behavioral interventions and environmental interactions on the behavior of the three types of people for the sustainability of energy-efficient buildings. The study also explored the impacts of behavior on the performance of energy-efficient buildings. Norouziasl et al. (2020) used sensors to predict the schedules of people and their lighting-related behaviors in an office building and simulated this environment through ABM, and finally explored effective ways to reduce lighting energy consumption. Klein et al. (2012) developed an AB multi-objective model to improve energy efficiency by scheduling meetings and controlling building systems while attempting to improve occupant comfort. Azar et al. (2016) and Azar and Al Ansari (2017) used ABM to develop a facility management plan to reduce energy consumption while improving occupant health and thermal comfort.

Green decisions by stakeholders also drive green and sustainable development in the construction industry. Mukherjee and Muga (2010) analyzed the influencing factors of decision-makers' adoption and dissemination of sustainable technologies in the construction engineering industry, and found that the acceptance of stakeholders is the key influencing factor. Stephan and Menassa (2015) studied the impacts of social networks on the decision-making of various stakeholders on their value. The research shows that the higher the degree of interaction of social networks, the more favorable the interaction of stakeholders. Different types of networks have different effects on the formation of consistency of sustainable renovation decision-making. Meng et al. (2018b) analyzed the interaction process between customers and manufacturers in the development of green building products and the changes in manufacturers' decisions. The findings indicated that customers' financial resources are positively correlated with manufacturers' green decisions, and customers have relatively high requirements for green products. Du et al.

Table 9. Classification of studies on sustainable development

Objective	Main dimensions and codes	Sub-objective	Representative literature
Sustainable development	(1) Construction waste management	Effective disposal of construction waste for environmental sustainability	Gan and Cheng (2015), Ding et al. (2016, 2020, 2021), Yu et al. (2021)
	(2) Construction energy consumption	Reducing energy consumption and promoting environmental sustainability	Klein et al. (2012), Rosales-Carreon and Garcia-Diaz (2015), Azar et al. (2016), Azar and Al Ansari (2017), Liang et al. (2019), Ali et al. (2020), Norouziasl et al. (2020)
	(3) Green decision-making	Some of the green choice preferences of stakeholders will drive the development of green buildings	Mukherjee and Muga (2010), Stephan and Menassa (2015), Meng et al. (2018b), Du et al. (2023)

(2023) investigated the effectiveness of PC strategies by introducing different cost reduction scenarios in the model to assess the effectiveness of different prefabricated construction (PC) policies with respect to the sustainability of decision making in the construction industry.

3.7. Coordination of multi-party relationships

There are many project parties involved into the operation of projects, and coordination is needed in order to manage their relationships and ensure that the goals of projects are achieved. Coordination is a certain organizational means and method to dredge relationships and remove the interference and obstacles within projects. The use of ABM methodology during the operation of a construction project can be a good way to regulate the relationships between multiple parties so as to achieve the pre-determined goals of projects. Current research has explored coordination from three main perspectives, which is shown in Table 10.

Some researchers have explored the coordination between organizations and the external environment by using the ABM method. Ke (2018) modeled and analyzed the evolutionary process of the transition from traditional migrant workers to industrial standardized workers in China in response to the coordination problem of engineering construction worker shortage. Liang et al. (2019) addressed the coordination problem of policy effectiveness by analyzing the impacts of incentive policies on the decision-making behavior of different owners and optimized three incentive policies on the platform. The study concluded that the agent-based policy works best. Singto et al. (2021) addressed the coordination of conflicting interests related to the construction of reservoir projects, simulated the process of the impacts of project construction on related farmers and the environment under the compensation strategy, and assessed ex-ante the income and satisfaction of farmers under different conditions through the model. Araya (2022) showed that multi-skilled workers as an alternative to the ongoing pandemic can optimize the progress of construction projects and labor shortages by quantifying the impact of multi-skilled workers on construction sites in the context of the pandemic.

Some researchers have explored coordination among project participating units (stakeholders) using the ABM method. Kim and Paulson (2003) proposed a new agent-based compensation negotiation method to facilitate "distributed coordination of project schedule changes (DCPSC)", in which a project can be dynamically rescheduled through the negotiation of all relevant subcontractors. Awwad et al. (2015) used an Anylogic simulation platform to simulate and analyze the impacts of the interaction between contractors in different construction bidding environments on contractors' bidding decisions, market equilibrium, and performance. The study also clarified the impacts of risk factors (such as risky behavior, risk attitudes) on the price increase strategies. Jo et al. (2015) analyzed the sudden and heterogeneous behavior of stakeholders for the dynamic coordination of project investments to explore the dynamic feasibility issues regarding the project and the practicality of the approach. Meng et al. (2018a) focused on the coordination of objectives in projects. The study simulated and studied the impacts of three types of fair preferences of contractors on project negotiation effect and negotiation income, and the findings indicated that different sympathy coefficients and jealousy coefficients have different effects on income sharing coefficients. Su (2020) analyzed the decision-making process among construction waste recycling process stakeholders and the elements affecting the coordination of strategies. On this basis, the authors proposed a tripartite subject game model. Hussein et al. (2022) investigated the impact of decision making on the performance of modular integrated construction supply chains (MIC-SC) in terms of duration, cost and emissions, and the coordination between these performance indicators.

In addition, several other researchers have explored the coordination between relationships within participating units using the ABM method. Son and Rojas (2011) explored the organization and coordination of temporary teams in construction. Based on the game theory and social networks, the authors simulated the evolution of collaboration among members of a construction project team. The research results showed that the efficiency of a collaborative network is affected by the establishment of the relationships between employees. Ahn and Lee (2015) explored the coordination of worker behavior and construction project performance. Based on questionnaires, the authors analyzed the influences of social norms on the group behavior of workers in construction projects and

Table 10. Classification of studies on coordination of multi-party relationships

Objective	Main dimensions and codes	Representative literature
Coordination of multi-party relationships	(1) Coordination between the organization and the external environment (e.g. coordination with policies, resources, factors of production, etc.)	Ke (2018), Liang et al. (2019), Singto et al. (2021), Araya (2022)
	(2) Coordination among project participants (e.g., coordination between owners, contractors, subcontractors, etc.)	Kim and Paulson (2003), Awwad et al. (2015), Jo et al. (2015), Meng et al. (2018a), Su (2020), Hussein et al. (2022)
	(3) Coordination within participating units (e.g. coordination between project departments, personnel, etc.)	Son and Rojas (2011), Ahn and Lee (2015), Mahjoubpour et al. (2018), Kedir et al. (2020), Akcay and Arditi (2022)

verified that the model can effectively improve worker behavior. Mahjoubpour et al. (2018) simulated and analyzed the influence of factors such as interaction and characteristics among employees of construction workers' learning behavior and the change of employees' working ability in the process. The research findings showed that the model helps to coordinate the relationships between learning behavior and performance in projects. Kedir et al. (2020) constructed the Multi-Criteria Decision Making (MCDM) and Fuzzy Agent-Based Modeling (FABM) decision-making models that help to improve the decision-making process in construction and help construction practitioners to adopt economically viable strategies to improve the motivation and performance of construction workers. Akcay and Arditi (2022) addressed the issues of liability identification and compensation coordination in construction accidents, and modeled the role relationship between workers and employers to quantify the negotiation of liability between the parties in an accident.

4. Discussion

On the basis of reviewing relevant literature, it was found that the application of the ABM method in the field of construction management is becoming increasingly popular. These studies can be linked to one of the construction management objectives. A close examination of these studies found that the historical research mainly focuses on the fields of construction safety, time, sustainability, and coordination. Few researchers are involved in the fields of cost, quality and risk, and therefore these three fields still need to be further explored in the future. Although it was recognized the contribution of using the ABM method in various sub-fields of engineering management, the research in these fields still has certain challenges. This section will discuss some common problems in the research, and propose potential and reasonable solutions to them.

4.1. Challenges and limitations

ABM has its advantages in portraying the intelligent decision-making, behavior evolution of heterogeneous agents, and macro emergence phenomena caused by interactions between agents. It also shows strong vitality in the application research of construction management. However, there are still some factors that hinder the further development of ABM method and reduce the effectiveness of the research method.

First of all, the experimental data used and the initial parameters set by researchers in developing the ABM model are mostly derived from self-recognition and empirical understanding of complex systems construction, and empirical data is rarely used to verify the accuracy of the simulation model (Ye et al., 2020). Such empirical data and insights will change due to factors such as different researchers or different types of projects, which will cause the results failing to meet the needs of different projects and the generality and effectiveness of the conclusions will also be weak. Meanwhile, the verification techniques (e.g., sensitivity analysis and factorial analysis) are insufficiently applied in the model validity verification, which results in the inability to fully study and consider the effects of data representation parameters and the interaction between different input parameters (Ding et al., 2016).

Second, when researching certain problems in the construction field, some unstructured factors may not be considered in the model. Nevertheless, these factors are essential for understanding and solving the problem. Although the model is a simplification of reality, the ability of research to guide reality will be insufficient or the research will be far from reality if some key factors are not taken into consideration. For example, when exploring the safety climate, it is difficult to estimate the intangible costs of employee morale and productivity loss, and employee turnover (Awwad et al., 2017). Some literature modelled the interactive behavior characteristics of agents, and rarely modelled other agent characteristics. Collective phenomena resulting from individual behavioral attributes are rarely highlighted in this literature. It means that the behavior rules or models between the subjects of the experiment in a simulated environment are relatively simple compared to the various connections in the actual production process, and their true complexity cannot be reached (Cheng et al., 2021). In addition, the subject's active behavior in the model is still in the reactive stage, and it has a low level of adaptability and learning ability (Ji et al., 2019). Moreover, its intelligence is far away from the level of people in real situations.

Finally, the scale of construction of major projects in countries around the world is increasing. Compared with general projects, the characteristics of major projects (e.g., wide area, complex natural environment, instability of project decision-making, large scale, and many types of construction subject groups) lead to the high complexity of construction management. Therefore, the research on the complexity of major construction management is becoming the mainstream (Sheng, 2018). However, the scale of the current ABM model cannot meet the requirements of complexity in real-world scenarios.

4.2. Future directions

In summary, to further promote the effective use of ABM in the construction management research, various improvements should be made.

(1) Data used by the model

Since actual data are difficult to obtain or cannot be measured, most of the current experiments or most of the data settings in the experiment are mainly derived from the researcher's hypothesis, empirical data, or borrowing from other literature and other channels. However, this may cause the initial value of the experiment to be far away from the actual value, or it is only applicable to a single project and has limited value for other projects. Therefore, researchers should work closely with the government, construction companies, or corresponding practitioners to analyze the collected actual or real-time data through technologies such as the big data analysis, cloud computing, and the global information system technology. This will provide information driving force for the hypothetical variables in the model and improve the fit between the model and the actual results. In terms of the validity verification of the model, researchers can not only use the verification techniques such as robustness analysis, sensitivity analysis, and structural validation to verify, but also consider the reference of real case studies or the feedback of expert judgments to further improve the authenticity and credibility. In addition, the data obtained from questionnaires and event-related potential experiments can also be used to test models to a certain extent.

(2) Intelligence of the agent

In the face of increasingly complex construction projects in practice, the learning, intelligence, adaptability of the agent in the model and the interaction mechanism between different agents, it is difficult to effectively portray the complexity of the system in reality. Therefore, when building a multi-agent model, researchers should integrate the theories and methods of various disciplines (e.g., social network analysis, machine learning, game theory, artificial intelligence, big data) to further improve the agent's intelligent decision-making ability and the ability of the model to depict the complexity of reality.

(3) Scope of ABM applied research

As the scale of major construction projects increases, the ABM technology will gradually be more integrated with major construction management complexity research in future research. The complexity of major projects is manifested in several aspects, such as the complexity caused by the openness of the environment, the complexity caused by the diversity of the subject, the complexity caused by the correlation of elements, and the complexity of the system structure. Besides the existence of complexity, major projects also involve a lot of uncertainties (e.g., probabilistic and subjective uncertainties). Therefore, the ABM technology itself (e.g., the comprehensiveness of the model, the intelligence of the agent) urgently needs to be improved through effective methods (e.g., computer technologies, interdisciplinary integration, fuzzy logic). To provide effective scientific guidance for major construction practices, there is a need to establish more complex, larger-scale, and more computationally capable models.

5. Conclusions

As an important factor affecting the sustainable development of the society, engineering construction is asking for higher requirements for construction management. The level of management will directly influence the achievement of multiple objectives and performance. However, due to the increase in the scale and complexity of engineering construction projects, construction management is facing many complex challenges. To clarify the mechanism of construction system complexity and improve the ability to control the complexity of construction management, scholars have used the ABM method in the research field of construction management.

Currently, as there is limited literature summarizing the application status of the ABM method in construction management research, a systematic and holistic understanding of this research field is still lacking. Therefore, this paper searched and reviewed 133 relevant literature sources retrieved from the WOS database. Based on the multi-objectives involved in the engineering construction process as the literature classification framework, this paper depicts the research status in the studied field. The CiteSpace mapping software was used to analyze the keywords co-occurrence, cluster and keywords burst detection diagram of these documents, which helps to clearly show the trends in this field. On this basis, the study suggested the application and improvement paths of this method from three aspects, including the scientific and validity of data, the intelligence of agents in the model, and the scale of the constructed model. The study provides a theoretical basis for strengthening the effectiveness and universality of the ABM method in the construction management research.

There are still some limitations in this study. First of all, the WOS database was adopted in this study. Although WOS has a relatively comprehensive range of world-class academic journals, books and conference proceedings, there is still a possibility that some relevant studies were not included in this review. Secondly, although some indicators were used to depict the existing relevant literature on using the ABM method in the construction management research, there are still some indicators that are not included in the study. On the basis of the multi-objective classification framework, there are some classifications that involve very little literature. Therefore, the study does not include them in the framework of the analysis.

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Author contributions

Wenyao Liu, Qingfeng Meng and Hanhao Zhi conceived the study and were responsible for the design the overall logical framework. Wenyao Liu, Hanhao Zhi and Xin Hu were responsible for literature collection and bibliometric analysis. Wenyao Liu, Qingfeng Meng and Zhen Li were responsible for the distillation of the core content of the literature. Wenyao Liu wrote the first draft of the article.

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