Applications of Multi-agent Systems from the Perspective of Construction Management: A Literature Review

Abstract

Purpose – The applications of multi-agent systems (MASs) are considered to be among the most promising paradigms for detailed investigations and reliable problem-solving methods, and MAS applications make it possible for researchers and practitioners to better understand complex systems. Although a number of prior studies have been conducted to address complex issues that arise from construction projects, few studies have summarised the applications and discussed the capacity of MASs from the perspective of construction management. To fill this the gap in the literature, this paper provides a comprehensive literature review of MAS applications from the perspective of construction management.

Design/methodology/approach – Web of Science and Scopus are the most commonly used international databases in conducting the literature reviews. A total of 86 relevant papers published in SCI-Expanded, SSCI and Ei Compendex journals related to the application of MASs from the perspective of construction management were selected to be analysed and discussed in this paper.

Findings – Based on the 86 collected publications, the utilisations of MASs to support the management of the supply chain and the improvement of project performance are identified from the perspective of construction management, the characteristics and barriers of current MAS applications are analysed, a framework for developing agent-based models to address complex problems is proposed, and future research directions of MAS applications are discussed.

Originality/Value – This review can serve as a useful reference for scholars to enhance their understanding of the current research and guide future research on MASs. The proposed framework can help build agent-based models to address complex problems in construction management.

Keywords: multi-agent system (MAS), agent-based modelling (ABM), construction management, literature review.

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1 Introduction

The rise of computation has generated a new field of knowledge called 'complex systems', and the interconnected and complex world also makes simple models no longer sufficient to answer many of the questions arise. Since complex systems show features of decentralisation and adaptation (Son et al., 2015), the multi-agent system (MAS) has developed rapidly in recent years based on its capacity to deal with complicated problems regardless of subject area (Liang et al., 2016). The MAS is an extension of distributed artificial intelligence (AI), and an assembly of two or more agents having homogeneous or heterogeneous architectures, with the agent perspective as the most important and special feature (Lv et al., 2021). An agent is an autonomous computational individual or object with special attributes and actions, and a common feature of MAS is that each agent acts according to certain rules of behaviours, policies or other social, economic and environmental factors (Macal, 2016; Wooldridge, 2009). As an approach of computational modelling, agent-based modelling (ABM) techniques are applied to study complex systems and model real-world phenomena in terms of agents and their interactions (Macal, 2016; Wilensky and Rand, 2015). Although agent-based models are a type of MAS, both communities have evolved in a mutually independent manner with little communication between them (Luna-Ramirez and Fasli, 2018). Currently, there is a transition from the rational actor and equation-based models to agent-based models, and the top-down macro decision-making gradually changes to bottom-up micro stimulation (Billari et al., 2006). An agent itself typically lacks the resources, information and capabilities to solve the whole problem; however, interactions among each identifiable agent provide aggregated attributes that can facilitate decision-making procedures (Motieyan and Mesgari, 2018).

Although a number of prior studies have been conducted to address complex issues that arise from construction projects, few studies have summarised the applications and discussed the capacity of MASs from the perspective of construction management. To fill this gap in the literature, this paper aims to provide a comprehensive literature review on existing studies on applications of MASs from the perspective of construction management. Current applications of MASs in the field of construction management are identified, characteristics and barriers of using MASs are analysed, a framework for developing agent-based models is proposed, and future research directions for exploring MASs are discussed.

2 Research method

2.1 Data collection

Web of Science (WoS) and Scopus are the most commonly used international databases in conducting the literature reviews. The search terms in the current study were ‘agent-based modelling’ or ‘multi-agent system’ + ‘construction management’. The ‘document type’ in the two databases was limited to ‘article’ and ‘review’, while the ‘language’ section was limited to ‘English’. The results from WoS were refined to domains of engineering civil, engineering industrial, engineering multidisciplinary, management, construction building technology and computer science interdisciplinary applications, while in Scopus, they were refined to engineering, business management and accounting, social sciences, decision sciences and multidisciplinary domains. These settings were chosen to retrieve original and review articles on applications of MASs from the perspective of construction management. After the duplicate results from WoS and Scopus were merged, InCites Journal Citation Reports 2019 and Ei Compendex Source List (January 2020) were consulted to identify the articles and reviews published in SCI-Expanded, SSCI and Ei Compendex journals. If an article was published in the abovementioned indexed journals, it was selected for further processing; otherwise, it was excluded. The abstracts of the collected papers were also read to exclude irrelevant papers. Thus, the authors sought to ensure that the publications were retrieved from recognised sources.

2.2 Data analysis

A total of 147 articles and reviews were identified after the duplicate results from WoS and Scopus were merged (as of August 2020). Based on the inclusion and exclusion criteria, 86 relevant papers published in SCI-Expanded, SSCI and Ei Compendex journals on applications of MASs in the field of construction management were selected for further analysis. Figure 1 illustrates the publications by year. Although the collected papers indicated that studies relating to applications of MASs in construction management began as early as 2003, it not until 2015 that more researchers began to focus on the topic.

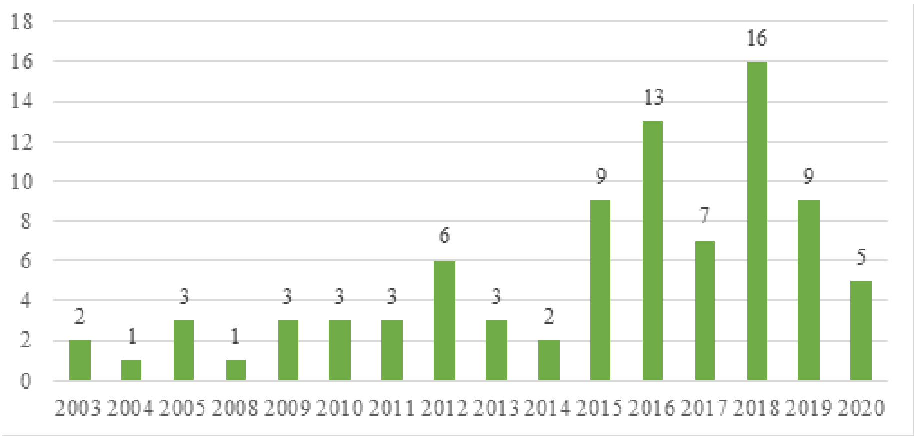

Figure 1. Distribution of selected publications by year

Table 1 indicates the journals that published at least two related studies. The journals that focused on information technologies in the design, engineering, and management of constructed facilities, such as Automation in Construction, Journal of Computing in Civil Engineering, and Journal of Construction Engineering and Management published more articles than the others, with 22, 12 and 10 such publications, respectively.

Table 1. Distribution of selected publications by journal

Journal	Quantity	Percentage
Automation in Construction	22	25.58%
Journal of Computing in Civil Engineering	11	12.79%
Journal of Construction Engineering and Management	10	11.63%
Engineering Construction and Architectural Management	4	4.65%

Complexity	3	3.49%
Safety Science	3	3.49%
Accident Analysis and Prevention	2	2.33%
Advanced Engineering Informatics	2	2.33%
International Journal of Interactive Multimedia and Artificial Intelligence	2	2.33%
International Journal of Project Management	2	2.33%
Journal of Civil Engineering and Management	2	2.33%
Journal of Management in Engineering	2	2.33%
Sustainability	2	2.33%

Table 2 shows the origins of the publications with the number of researchers, universities or research institutes, and involved articles. China and the USA contributed the most to applying MASs to the construction management domain; the number of papers and research institutions is the same for these two countries, although more researchers from China are engaged in the studies than in the USA. Apart from China, Iran is the other developing country that has comparatively high performance in promoting related research. Considering the construction industry scale, such results are logical.

Table 2. Origins of publications

Country	Researchers	University/Institute	Papers
China	78	23	28
USA	57	23	28
Canada	23	4	9
Iran	21	6	7
Korea	13	8	6
UK	11	5	5
Australia	11	4	6
Malaysia	10	3	3
France	9	3	2
Egypt	6	1	4
Germany	6	3	3
Lebanon	6	2	4

Greece	4	2	1
Singapore	4	1	2
Serbia	3	1	1
Sweden	3	2	2
Switzerland	3	2	2
Colombia	2	1	1
Hungary	2	1	1
Netherlands	2	2	2
Turkey	2	2	2
Algerie	1	1	1
Palestine	1	1	1

3 An overview of MAS applications from the perspective of construction management

Construction management is defined as “management of the development, conservation and improvement of the built environment” (CIOB, 2010), and it is a “professional service that provides a project’s owner(s) with effective management of the project's schedule, cost, quality, safety, scope, and function” (CMAA, 2021). Construction management addresses effective planning, organisation, application, coordination, monitoring, and control and can be clarified as the macro and micro levels: The macro level covers all management-related issues on the built environment across its life-cycle stages, while the micro level focuses on specific issues relating to project delivery at various work stages (Chen, 2019; Harris et al., 2021).

According to the collected publications, applications of MASs from the perspective of construction management can also be categorised at the macro and micro levels. The macro-level applications deal with issues regarding the behaviours of urban residents and address policy implementation and emergency response issues, while at the micro level, MAS applications provide support to the supply chain management process and assistance towards improving project performance. Figure 2 illustrates the two-level applications discussed in this paper.

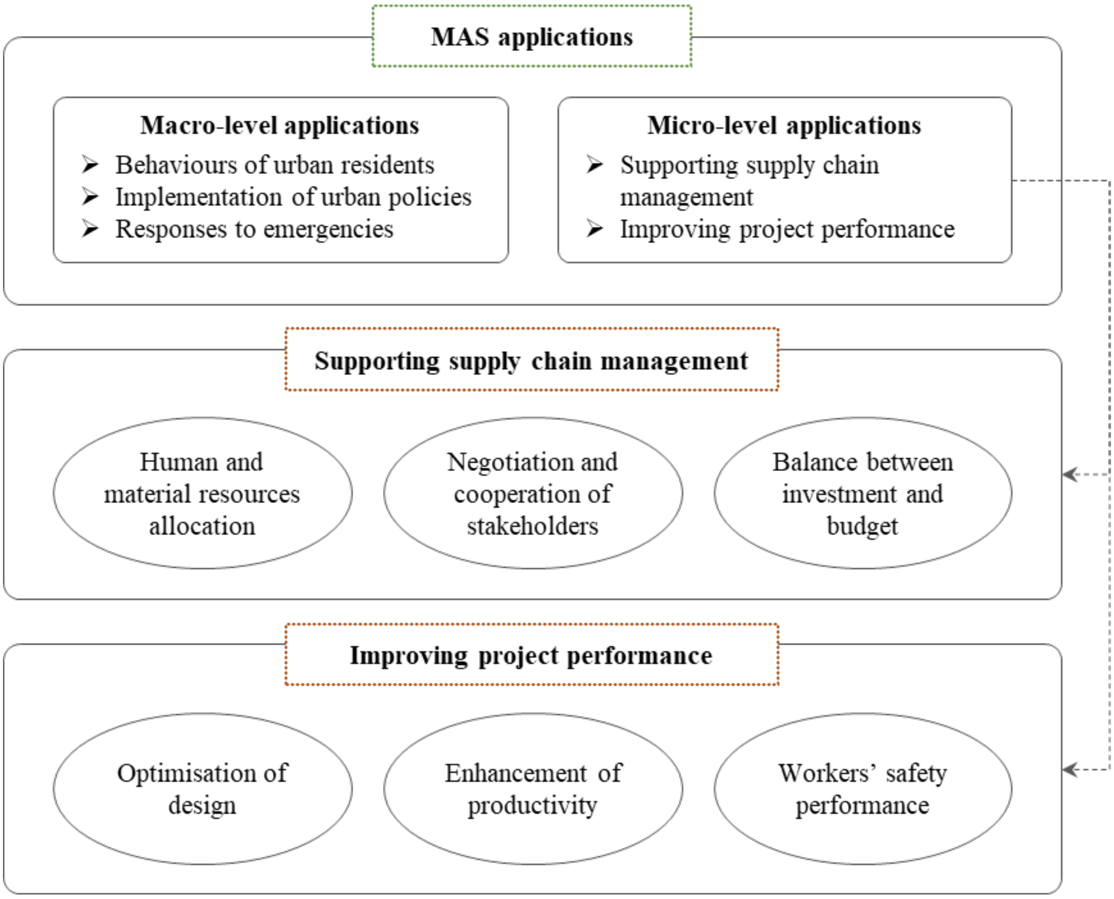

Figure 2. Two levels of MAS applications

3.1 MAS applications at the macro level

Urban planning and management research typically considers behavioural principles from a broader perspective. Urban planning is an interdisciplinary field that includes civil engineering, architecture, design sciences, politics, social science and human geography. Practitioners in this field are concerned with issues arising from urban design, public consultation, and policy implementation processes (Taylor, 1998). Urban management deals mainly with planning, governance, and regulatory issues, the success of which can further promote the development of construction management (Ding and Lai, 2012). The application of MAS is suitable to explore urban-level issues, especially to guide the land use planning and to assist in the implementation of urban policies. In addition, MASs are often applied to model the evacuation process, which would strengthen the later-stage management of construction projects.

3.1.1 The behaviours of urban residents

With the acceleration of urbanisation worldwide, growing attention has been given by scholars and practitioners to making cities better places in which to live. The question of liveability involves various factors, including but not limited to government policies, residents' behaviours and the allocation of facilities (Pan et al., 2020a; Pan et al., 2020b). ABM simulation is suitable to study relevant issues of urban residents' behaviours, which can be used to guide land-use planning. On the other hand, land use planning would influence the site survey and analysis in the design phase of the whole life cycle in construction management. To some extent, urban planning assists urban management which also includes construction management. Therefore, in the process of continuous development of urban construction, the application of the ABM method to solve problems such as urban residents' behaviours and decision-making is very helpful to the development of construction management. To explore the residents' behaviours, Goldstein et al. (2004) used an ABM approach to recreate the annual urban extent from 1929 to 2001 of Santa Barbara, California, in the USA, which described the dynamics and patterns of urbanisation. Cellular automata (CA) is a kind of automata that has become particularly popular in urban simulation in recent decades, and it is helpful to represent landscapes and infrastructure (Torrens, 2003). In comparison, MAS does better in illustrating mobile entities but the rules designed therein are not always appropriate for representing infrastructure (Torrens and Nara, 2007). Therefore, Torrens and Nara (2007) combined CA and MASs to develop a model of inner-city gentrification to represent human behaviours in complex urban systems based on a theoretical foundation that could cater to supply and demand determinants. Osman (2012) used ABM to represent interactions among users, assets, system operators and politicians and indicated how socio-technical aspects could be included within the complex decision-making process of urban infrastructure management. Czamanski and Broitman (2018) built a biology-inspired framework as a basis for the MAS of cities to analyse urban dynamics and obtained a variety of growing patterns. Furthermore, Pan et al. (2020a) explored changes in safe liveability in complicated urban systems and concluded that a rapid population increase would have a significant impact on safe urban liveability.

The understanding of settlement patterns of the past, as well as the connection of such patterns to the future, can guide urban planning in a more informative way. For example, Shirzadi Babakan and Taleai (2015) developed an agent-based model to study the relationship between transportation and the residential choice of households in Tehran, Iran. They found that transport development scenarios significantly affect residence choice and lead to significant changes in residential demand, composition of residents, mean income and car ownership levels. Alghais et al. (2018) conducted targeted surveys among Kuwaiti citizen and noncitizen groups regarding migration likelihood, push and pull factors, spatial preferences for new cities and their opinions on segregation by nationality. Useful answers were extracted and transferred to an agent-based model to simulate residents' involvement in urban planning. Peña-Guillen (2019) devised a network-based analogy of consolidation that allowed for dynamic simulations to be conducted using the ABM technique and generate consolidation processes in consideration of spatial and social dimensions in Lima, Peru. Marini et al. (2019) proposed and coupled an agent-based dwelling model to an agent-based population model to explore the evolution of features with regard to the demands of the population and the supply of the housing stock in Lausanne, Switzerland. The models employed were designed to facilitate the decision-making of urban planners and real estate investors seeking to lower risks and make cities more attractive.

3.1.2 The implementation of urban policies

The implementation of policies includes many options, and the MAS has been found to be a powerful tool to model scenarios and evaluate different outcomes before making a decision. Therefore, the MAS has been applied by stakeholders to address potential issues arising from the implementation of policies at the urban level. For example, Mukherjee and Muga (2010) introduced an agent-based model that allowed initial experiments to illustrate the importance of adaptive organisational behaviour under different professional networks and identified two main challenges to adopt sustainable practices in the architecture, engineering, and construction industries: the lack of a shared paradigm and the inability to consider adaptive forces. Kong et al. (2017) integrated CA and ABM to explore the impact of new satellite towns and ecological sensitivity on land-use changes, and their results demonstrated that both satellite towns and ecological sensitivity had greater impacts on urban expansion. Although CA is extensively used in simulating urban growing issues, it is limited because it can only deal with the self-organising expansion of a city (Kong et al., 2017). By integrating ABM into CA, researchers can obtain more accurate simulation results (Ma et al., 2018). Therefore, Ma et al. (2018) applied a combined CA and ABM model to describe the effects of implementing a linked urban-rural construction land policy in Tianjin, China from 2005 to 2020, concluding that such policy implementation could both alleviate the occupation speed of arable land and slow the fragmentation of large arable land patches. Motieyan and Mesgari (2018) developed an agent-based model that represented interactions between land use and transportation, in comparison with the detailed plan for the Tehran municipality in Iran, the assessment results indicated that the application of the model decreased differences between the transit-oriented development level and the public transit infrastructure level by 64 per cent.

Specifically, in regard to the policies of retrofitting buildings, Stephan and Menassa (2015) developed an agent-based model to explore how social interactions among various stakeholders would help prioritise values and ultimately facilitate optimal decision making on retrofitting a commercial office building. The results indicated that highly connected network structures could facilitate interactions among stakeholders to achieve alignment. Liang et al. (2019) defined the government and residents as agents and modelled their decision-making behaviours regarding the energy-efficient retrofitting of buildings using principle-agent theory. In this study, a platform based on the model was developed, and the incentive policy was optimised under different circumstances in China. Nägeli et al. (2020) presented a model to explore energy demand and greenhouse gas emissions of building stocks, especially with regard to how owners' decisions about retrofitting building envelopes and replacing heat systems would affect the development of building stocks in Switzerland according to data generated from 2000 to 2017.

3.1.3 Responses to emergencies

Despite technological advancements in the architecture, engineering, and construction industries, emergencies in buildings and other public spaces have consistently resulted in fatalities of a greater magnitude than those caused by all other types of natural disasters combined. Therefore, issues regarding responses to emergencies, especially evacuation procedures in buildings that are closely related to construction management, have attracted researchers' attention and MASs are often applied to model the evacuation process. For instance, Shi et al. (2012) investigated evacuation processes in various fire cases of fires with measurement data as input of the model and discussed the features of occupants' evacuation behaviours, evacuation time, passage flow rate, and strategies for using an escalator as an evacuation passage. Mirahadi et al. (2019) developed a framework by integrating the ABM, fire simulation tools and building information models (BIMs). The study's proposed framework was designed to help designers evaluate evacuation safety performance and analyse a building layout in BIM under various fire scenarios, which would ultimately result in design optimisation based on multiple safety criteria.

In addition to buildings and public spaces, some researchers focus on labour evacuation planning for construction sites; because these sites are highly complex and uncertain, incidents such as fires can easily lead to casualties. Thus, both risk assessment and evacuation process analysis are fundamental to construction safety management (Hua et al., 2020). The evacuation conditions in such places are quite different as there are always many temporary works on-site and the number of occupants, spaces and routes for evacuations change daily. Building in different construction scenarios and taking continuous space, discrete-time and modified social force into consideration, Marzouk and Daour (2018) used BIM and MASs to present a framework, which was implemented in an Egyptian social housing project. The study's proposed framework could calculate the total evacuation time on each floor and flight of stairs until the assembly point was outside the location and investigate ways for workers to leave the site safely.

3.2 MAS applications at the micro level

At the micro level, the construction management process focuses more on identifying, analysing and evaluating risks and promoting cooperation among team members, which is an important factor that contributes to project success. Construction projects are influenced by numerous types of hazards, such as organisational, human and economic. Objectives are not always achieved as such hazards cause projects to be plagued by cost overruns, delays and poor performance (Taillandier et al., 2015). However, the complicated factors that are inherent to construction projects, such as the multiplicity of stakeholders and the impact of various hazards, present many challenges to the management process. From the construction management perspective, almost all projects contain complex systems as multiple stakeholders work together and generally concentrate on different priorities. Construction projects are also characterised by a co-evolution of developments and processes based on self-modifications, meaning that the value of a certain project is set in the initial stage but will continue to develop throughout the whole project lifecycle (Son et al., 2015).

Therefore, ABM simulation as a bottom-up approach, which takes each agent, its behaviour, and interactions with other agents in a dynamic environment into consideration, would be particularly helpful in stimulating, identifying and analysing issues arising from stakeholders with different backgrounds or that belong to geographically separated teams and work in a dynamic environment. According to the publications generated, MASs can be utilised in different stages during the lifecycle of construction projects. Figure 3 depicts when and how the applications of MASs can address the different types of issues.

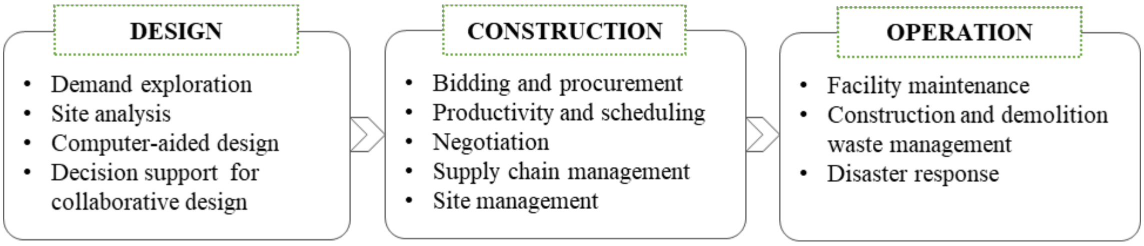

Figure 3. MAS applications in different stages of construction projects

Construction researchers and practitioners have tried to use various techniques to study complicated systems. The applications of MASs began in the early 21st century when computer-aided design in the construction area was experiencing significant enhancements, which also poses challenges to researchers and practitioners to identify how MAS can work effectively with other simulation and modelling approaches. More attention was paid to MAS applications after 2015, with particular focus on the management of supply chain and improvement of project performance, which is described in the sections below.

4 Utilising MASs to support supply chain management

Construction projects are described as long supply chains that extend across various products or service types and interests. Supply chains can significantly affect construction projects due to their ability to deliver construction products (Min and Bjornsson, 2008; Tah, 2005). Supply chain management philosophy has been widely accepted as both an effective and efficient approach to improving construction performance as it helps in the coordination of the distributed decisions of organisations and/or participants regarding flows of material, information, humans and cash (Xue et al., 2005).

4.1 Allocation of human and material resources

Construction projects are labour-intensive, and human resources account for 30 to 50 per cent of the total expenses of such projects (Hanna et al., 2007). Unlike materials and equipment that are typically obtained based on the market price and are beyond the control of project managers, labour costs are the least reliable factor and may be obtained at lower costs through efficient management once the related effects of the factors are understood (Dabirian et al., 2016). Under such circumstances, workers' behavioural diversities are explored by researchers.

Ahn et al. (2013) developed an agent-based model that incorporated mechanisms of workers' formal and social learning to extend the knowledge of workers' absence behaviour. They further suggested how real data collected by questionnaire surveys could be used to simulate workers' behaviours (Ahn and Lee, 2015). Mahjoubpour et al. (2018) studied workers' learning behaviour in a steel structure project and concluded that the social ability to teach and the workers' forgetting factors had major impacts. Wu et al. (2019) developed an integrated ABM and system dynamics (SD) model following a set of implementation approaches to reveal labourers' behavioural diversities and to evaluate their impacts on multinational and cross-cultural projects. That study found that such diversities dramatically affect labourers' productivity, work quality and absenteeism rate, resulting in severe project deviations if not adequately considered. Dabirian et al. (2016) confirmed that the impact of effective factors on the workflow could be predicted as an emergent property based on the interactions among workers, their tasks and the construction sites. Raoufi and Robinson Fayek (2018) proposed a methodology for integrating fuzzy logic and MASs to predict crew motivation and performance and then validated the model using field data collected from a company that was active in various industrial projects in Canada.

MAS applications in dealing with material allocation problems often focus on the equipment and materials applied during the operation, maintenance and demolition stage of projects. For example, Dibley et al. (2011) introduced a MAS for facility management that would alleviate the dependency of specialist users, as the system simply required an IFC specification for building and sensor locations. Shen et al. (2012) presented a conceptual framework of the agent-based service-oriented integration method to generate lifecycle information, with a specific focus on facility operation and maintenance management. Soroor et al. (2012) focused on single-product decentralised supply chains and used the ABM method to select the best supplier within the bidding system. Intending to elaborate how to enhance the recycling of construction materials, Knoeri et al. (2014) utilised MASs to examine Swiss construction actors' decisions and interactions, analysed key factors that would affect the demand for construction materials and developed scenarios that would lead to the maximal reuse of construction and demolition waste. Gan and Cheng (2015) conducted a comparative study with both mathematical programming and ABM approaches to identify an appropriate method to analyse the dynamic network of a backfill supply chain by implementing optimisation for backfill recovery among construction sites and a reduction of construction wastes disposed to landfills. Ding et al. (2016) measured and assessed the environmental impact of demolition waste management, and identified the significance of stakeholders' interactions and attitudes, as well as their utilisation of green demolition technologies.

4.2 Negotiation and cooperation among stakeholders

Research has been conducted to address related to the conflicts that often occur in the context of cooperation among multiple stakeholders. Xue et al. (2005) designed an agent-based supply chain management coordination framework and integrated organisations into a construction supply chain. The framework was further extended by presenting a relative entropy method to improve the efficiency of agent-based negotiations, especially when prior negotiations failed, or automatic search processes were terminated (Xue et al., 2009). Tah (2005) presented a case with an ABM simulator that allowed organisations to understand the dynamic interactions and interdependencies of supply chains prior to the implementation of management practices. Min and Bjornsson (2008) emphasised the value of real-time information and used an agent-based construction supply chain simulator to demonstrate human-to-human and computer-to-human interactive simulations. El-Adaway and Kandil (2010) used a formal logic algorithm to simulate the process of legal discourse in construction disputes, presented a theoretical foundation and technologies to generate legal arguments related to construction disputes and applied ABM for resolution. Son and Rojas (2011) introduced an agent-based simulation to evaluate collaboration in interorganisational networks of construction project teams based on game theory and social network perspectives. Du and El-Gafy (2012) proposed the usage of MAS to explore the interactions between human and organisational factors, and the results indicated the need to understand the social and managerial effects of construction processes. Taillandier et al. (2015) proposed a stochastic multi-agent simulation model used to simulate project progress when integrating the causes of possible risks and their impacts. Hsu et al. (2016) utilised the MAS to explore the complexity of project team member selection, suggesting that managers should be aware of how interdependent relationships were distributed across a cohort before engaging in any reorganisations. Taillandier et al. (2016) used the MAS to develop a simulation tool that considers risks to assess consequences for each stakeholder of a construction project, and they presented an application to a real case-study at Tlemcen, Algeria. Zhu et al. (2016) used bargaining game theory and time-dependent negotiation strategies with a learning-based method in an agent-based debt terms' bargaining model to simulate the negotiation process and to improve the efficiency of public private partnership (PPP) projects.

Although a growing number of scholars have applied MASs to investigate issues of cooperation and negotiation, the separately developed models inevitably lead to duplicate development efforts as well as inconsistent theoretical foundations. Therefore, Du et al. (2016) proposed a sharable, universal and open-source database of behaviour models that contain cooperative behaviours in relation to construction problems, and they proved its usefulness for investigating cross-functional cooperation in an engineering, procurement and construction projects.

4.3 The balance between investment and budget

Several studies concentrate on the bidding and tendering process of construction projects when exploring investment- and budget-related issues. As contracting firms always face the challenge of selecting a sufficiently low bidding price to win a project and a sufficiently high price to make a satisfactory profit, Asgari et al. (2016) employed ABM to simulate the bidding process and defined makeup behaviours within a market form of contractors. Kog and Yaman (2016) proposed an agent-based contractor prequalification model to support a client's decision on contractor selection in the context of a tender management system that contained open, selective limited and negotiated tendering processes. Awwad et al. (2015) presented an agent-based model for the competitive construction tendering process that allowed observation of the bidding process dynamics: contractors with different characteristics and attitudes competed over projects, learned about others' competitiveness and made bidding decisions. This work was further elaborated by addressing the owner's concern about choosing suitable bidding methods by simulating the construction bidding process dynamics of alternative piece-driven tendering approaches that would preserve the transparency of the low-bid method, and rectify the inconvenience of unrealistically low bids (Awwad and Ammoury, 2019).

Other works are typically case- or scenario-based studies. For instance, Jo et al. (2015) discussed the feasibility of public investment projects with ABM and SD and applied the hybrid model in a bridge construction case. Farshchian et al. (2017) simulated the budget allocation and its effects on projects' progress in various scenarios, including cancelling, suspending or slowing down projects and evaluated project behaviour. The proposed model was designed to help organisations reduce concerns about their portfolio, generate income from projects, and obtain the results of budget limitation strategies more quickly. Farshchian and Heravi (2018) also simulated different conditions and scenarios considering cost inflation during the execution period of construction projects, and they evaluated the model with a theoretical portfolio that contained 50 projects. Meng et al. (2018) adopted a lifecycle perspective and built an agent-based revenue-sharing negotiation model to focus on time compression. They identified the degree of sympathy preference in inequity aversion, which was found to have an important impact on the time required to reach a consensus, while the degree of jealousy preference showed no obvious impact on the time required to reach a negotiation agreement. They further incorporated the contractor's competitive and social welfare preferences into the negotiation game model. The experimental results of that study showed that competitive preferences would make the agent pay more attention to his or her gains and revenue in the negotiation process, while the sympathy component of the social welfare preference had limited influence on the revenue-sharing coefficient (Meng et al., 2019).

5 Employing MASs to improve project performance

The success of a project is identified to connect with both efficiency and effective measures. The former corresponds to strong management and an internal organising structure, and the latter refers to user satisfaction (Takim and Akintoye, 2002). The MAS is found to be useful for simulating unforeseen conditions and uncertainties that result in schedule delays and cost overruns and for proposing strategies to deal with problems related to project performance.

5.1 Optimisation of design

Modern architectural and site layout design are influenced by the availability of technology, and the development of construction techniques not only enlarges boundaries but also enables different types of design in both theory and practice (Agirbas, 2019). Architectural and site layout design are immensely complicated and have experienced an increase in the methods to generate, rationalise and optimise processes and outcomes. Utilisation of the MAS might aid the design process specifically in the drafting phase (Gerber et al., 2017).

Porter et al. (2014) introduced MAS implementation of BIM for the assessment of infrastructure security and showed that the ABM technique was helpful for both the analysis and design of facilities. Páez-Pérez and Sánchez-Silva (2016) developed an agent-based simulation model to trace an interaction history within the context of a PPP among the principal, agent, and natural environment and its effect on the infrastructure system, and they calculated the utility for each player. Gerber et al. (2017) developed an integrated design methodology based on the MAS that provided designers both geometric and multiple performance feedback, assisting them in selecting among design solutions. Younes and Marzouk (2018) developed a detailed agent-based model for the operation of tower cranes that can help in the planning and optimisation of the number, types and locations of tower cranes as well as in the evaluation of the effect on execution time. Du et al. (2019) proposed a decision-making evaluation model based on the MAS that considered the dynamic characteristics of design change risks for the whole process of a prefabricated construction project. Song et al. (2019) simultaneously incorporated decisions from the layout planner, the logistics planner and the safety manager to examine the interactions in the determination of an optimal site layout plan, and they validated the agent-based model through a case study. Agirbas (2019) investigated swarm intelligence based on the mathematical rules for the possibilities involved in architectural design and façade construction and compared façade designs in different geometries via multiagent-based swarm intelligence algorithms. Liu et al. (2020) proposed a multiagent reinforcement learning system with BIM for path planning, considering both immediate and delayed rewards in clash-free rebar designs for real-world reinforced concrete structures.

During the building design stage, especially for high-rise projects, the parameters for the elevators are quite important, as their capacity and running speed should be considered to satisfy future needs and MASs can be used to help analyse lift system performance. Jung et al. (2017) used simulation experiments with seven lift options and examined the relationship among system performance, lift car service range and lift traffic type. Xiang et al. (2019) proposed a hybrid elevator planning model that combined discrete-event and agent-based simulations to obtain the average waiting and spending time related to up-peak scenarios during a typical day.

5.2 Enhancement of productivity

The length of the construction period has significant effects on the economic, social, and ecological benefits of certain projects, and productivity is one of the factors that most influence the time required for a construction project. Several studies focus on the congestion issue, which causes expensive inefficiencies in work and labour flows that negatively affect performance. More specifically, Watkins et al. (2009) discussed the relationship between congestion and productivity by representing workers and tasks as agents and developing the mathematical formalism to study their interactions. The results indicated that congestion at a construction site could be considered an emergent property. Kim and Kim (2010) developed a MAS to simulate construction operations and applied it to earthmoving activity, considering the traffic flow of the equipment with the congestion of construction vehicles that would affect work efficiency and productivity. A similar study was also carried out by Jabri and Zayed (2017) to capture the properties and interactions of model elements, which they verified with a real-world case study. Zhang and Hammad (2012) proposed a MAS that integrated motion planning and real-time environment updates to improve crane operation safety and eliminate delays caused by unpredicted spatial problems at the construction site to improve productivity. Marzouk and Ali (2013) proposed a model to estimate bored pile productivity considering safety requirements and space availability. Unsal and Taylor (2011) combined MASs with game theory and explored whether precontract partner selection strategies would lead to holdup problems, especially those concerned with relationship-specific investments in learning after the introduction of an innovation or organisational change throughout a project network. Khanzadi et al. (2018) proposed a hybrid simulation tool, which they implemented in a real concrete project using the SD tool to simulate various continuous factors affecting labour productivity and the ABM tool to explore the congestions that arise from interactions among different working groups.

Other related studies have discussed improvements in productivity in terms of specific construction elements. For instance, Matejević et al. (2018) presented an original model with ABM and discrete event simulation methods to predict the productivity of reinforced concrete slabs. Wang et al. (2018) embedded the heuristic optimisation algorithm within a MAS schema to synchronise the production scheduling and resource allocation. Implementation of the model indicated that it would help project managers predict and improve the value of labour productivity. Abou Yassin et al. (2020) stimulated and optimised the printing of retaining and shear walls, identifying a larger gap between the capacity of concrete and steel 3D printing that mainly resulted from the slow rate of steel printing or welding.

5.3 Workers' safety performance

In addition to the issues related to workflows and products, safety performance is another factor that can impact both the cost-efficiency and the performance of a construction project. It is a general belief that the more safety investment there is, the better the safety performance of a project. However, this belief is also one of the main factors that have led to the construction industry's reputation for poor safety records (Awwad et al., 2017).

Unlike the top-down approach that starts with a theory of the relationship between safety investment and performance followed by researchers' specific hypotheses to be tested with equation-based modelling methods, Goh and Askar Ali (2016) utilised a hybrid framework to represent the various components of construction activities and conducted a hypothetical earthmoving case study to show that safety behaviours can be considered during planning. Choi and Lee (2018) developed an agent-based model that incorporated the socio-cognitive process of workers' safety behaviours and demonstrated that safety management interventions such as the strictness and frequency of management feedback and project identification contributed to decreasing the incident rate. Li et al. (2018) built a three-layer model that included system performance, agent interaction and agent attributes to study the unsafe behaviours of construction teams and to manage the challenges of complexity through a case with a realistic background. Lu et al. (2016) provided a practical framework by using the MAS to investigate how safety investments with different parameters could affect safety performance. The results of that study illustrated that proactive construction management system assistance, safety supervisors' inspection and coworkers being responsible for one another's safety were three effective investments towards improving safety performance. Awwad et al. (2017) presented an agent-based model that combined stakeholders in a market environment and explored their interactions in the bidding and construction stages of a project. That model made it possible to observe emerging safety patterns in a given environment based on the potential reformative actions initiated by various stakeholders. Zhang et al. (2019) modelled on-site interactions between workers and management teams, distinguished marginal behaviours at multiple levels, associated worker behaviours with their respective backgrounds, and recognised the impacts of such heterogeneity on the overall safety performance of a construction team. The results of that study led to the suggestions that management teams should emphasise and cultivate the leadership role among supervisors and that senior managers should regularly be involved in safety activities. Ji et al. (2019) simulated workers at a construction site with a crane hazard, and the results indicated that combined coworker support actions, such as warning coworkers to leave hazardous areas and reminding them to wear personal protective equipment, could effectively reduce the severity of recordable, lost-time and fatal incidents, whereas a single measure would be more likely to work when nonfatal incidents occurred.

6 Discussions

6.1 Characteristics and working mechanisms of the MAS

The way to conceptualise and model construction systems has changed from aggregate to disaggregate and from static to dynamic (Crooks and Heppenstall, 2012), and the desire to model the world in a way that is more faithful to the real world has motivated the development of MAS and applications of the ABM technique (Macal, 2016). Given that current AI systems face the challenge of integration, not only how to integrate diverse techniques, but also how to preserve conceptual integrity when highly heterogeneous methods are put to work together, the MAS provides a sound foundation to address integration issues and to design AI systems (Calegari et al., 2021; Shojaei et al., 2018). The MAS also shows its worth in supporting system modelling for consequential assessment by forecasting the interaction between the production and consumption system (Micolier et al., 2019; Okakpu et al., 2019). Agent-based models are flexible, process-oriented and obtain more detailed simulation results than equation-based models (Lv et al., 2021; Son et al., 2015). To be more specific, 'flexible' refers to the idea that the MAS can capture a variety of behaviours for agents, operate when decisions are made based on probability, and at the same time maintain a balance between flexibility and precision; 'process-oriented' represents a focus on how agents apply information and interact with each other and the environment, which is usually ignored by equation-based models that rely on parameters to abstract problems; and 'detailed' refers to the results generated by MASs on both the individual and aggregate levels, since the agent-based models operate by simulating each agent and their decisions.

Based on current applications of MASs and the ABM technique discussed in this paper, when a system involves multi-human or multi-organisation decision-making in the transition, and the status is significantly determined by the relationships among multiple agents, the MAS will be of great help. Since the MAS can act separately and be executed by numerous agents, it is suitable for complex interactions, including cooperation, coordination and consensus. The MAS is also robust because it does not rely on a centralised control centre. Hence, a complex problem can be divided into smaller problems and be assigned to multiple agents for parallel processing (Liang et al., 2016), especially when individual behaviour is nonlinear and the interactions of agents can generate network effects (Bonabeau, 2002). The MAS is also helpful when the decision-making process is not purely technical but includes social and political needs and constraints that should be embedded rather than modelled as externalities (Osman, 2012). In addition, the ABM technique can be utilised to identify a suitable level for exploration, when the complexity of a system is unknown as it provides a framework to integrate the complexity of agents.

6.2 A framework for developing the agent-based model

The five-step framework proposed:

After careful analysis and generalisation of the current applications of MASs presented in this paper, a five-step framework can be followed to develop the agent-based model when dealing with complicated issues in the construction area. Figure 4 illustrates the five steps starting with (1) the problem statement, followed by (2) multi-agent confirmation, (3) agent-based model establishment, (4) experimentation and model validation, and ending with (5) model application. Feedback from the last two steps will be given to the third step; thus, the agent-based model can be more reliable and persuasive.

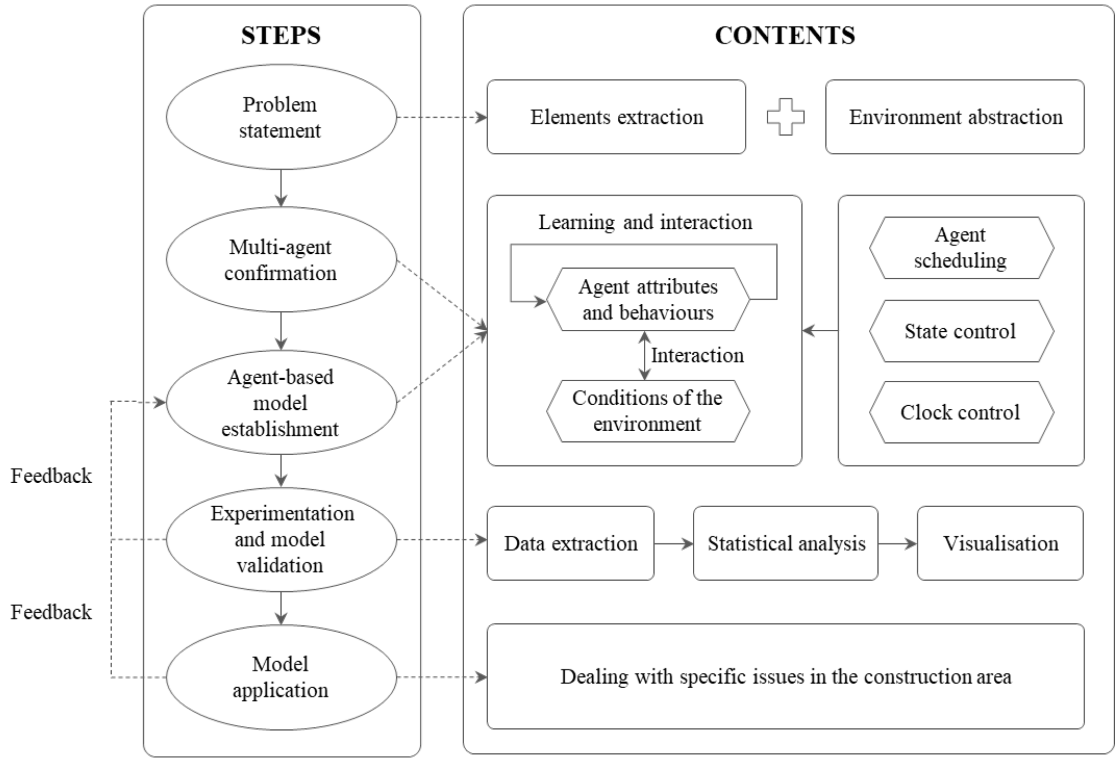

Figure 4. A framework for developing agent-based models

The cross-validation of the proposed framework:

The five-step framework to develop an agent-based model has echoed previous studies conducted from the perspective of construction management. The problem statement step requires a detailed description of both conceptual and practical situations, as challenges from the perspective of construction management are typically diverse and complicated. In this step, heterogeneous elements and entities applied in the model are extracted and reviewed, and the associated physical environment is abstracted (Lai and Liao, 2013). During the multi-agent confirmation step, after identifying the problem to be approached, the attributes and behaviours of multiple agents, together with the conditions of the environment can be determined (Shou and Lai, 2011). The combination of the existing literature and practical facts, such as the characteristics, features and roles of the entities and surroundings, serve as references for the multi-agent confirmation step. For example, Choi and Lee (2018) conducted an empirical study to determine the role of the sociocognitive process and its interaction with the environment in shaping workers' safety behaviours. Information sharing and interactions among agents, together with the interactions between agents and the surrounding environment, serve as the core of the agent-based model (Araya, 2020). The attributes, behaviours and interactions referred to above should be computer understandable. The identified agents have different self-learning and self-organising mechanisms based on specific operational regulations, and each agent connects with others through information interactions (Pan et al., 2020a). Within a continuously changing environment, agents can generate various behaviours and make different decisions. The connections among multiple agents themselves and interactions between agents and the surrounding environment create a complicated dynamic system.

The control unit in the second and third steps is used to ensure the smooth operation of the MAS, with the agent scheduling section used to allocate resources for agents, the state control section used to monitor changes in each element in the system, and the clock section used to ensure that the system runs under certain time sequences, such as days, months or years (Pan et al., 2020a). It should be noted that the agent-based model obtained from the third step is an initial model that needs to be adjusted and verified (Ben-Alon and Sacks, 2017). During the experimentation and model validation step, simulations are carried out and the data obtained from this step are analysed by statistical methods and visualised mainly using tables and diagrams (Choi and Lee, 2018). Basic real-world data are necessary to ensure that the outcomes of reality and the model are consistent. For instance, Jung et al. (2017) validated the simulation model through experiments by comparing the outcome of the simulation with 72 data samples observed from actual systems. Some practical problems may include various agents and result in a large-scale model; thus, an appropriate mechanism is necessary to ensure that the model can operate with appropriate running time and storage space. Related analysis results are employed to adjust the former two steps before applying the model to address specific issues from the perspective of construction management. Ben-Alon and Sacks (2017) authenticated the simulation tool by testing predictable scenarios, which resulted in similar patterns to those found in an actual construction site. Thus, it is more reliable to apply this simulation tool to explore emergent outcomes of more complex scenarios. Overall, each step of this framework has been cross validated by previous studies. In general, by summarising the previous literature, an effective improvement of the agent-based model makes complex problems easier to solve; however, this model still needs further studies to verify its universality.

6.3 Barriers in current MAS applications and future research directions

MAS applications are gradually accepted by researchers and practitioners from the construction management field; however, there are some contexts in which the cost of building an agent-based model exceeds the benefits. First, applying the ABM technique could be more costly and time-consuming than researchers and practitioners might imagine (Klügl, 2012). To be more specific, the high computational requirements of ABM remain a problem in regard to modelling large systems. Simulating the detailed behaviours of underlying agents can be extremely intensive in computation and therefore become time-consuming (Bonabeau, 2002; Zheng et al., 2013). Second, the abstraction of a certain phenomenon requires careful consideration; if the level of abstraction is too simple, then important variables may be ignored, but if too many details are included, then the model may have a larger number of constraints and become excessively complex (Crooks and Heppenstall, 2012). Third, even though the power of computing increases, the high computational requirements of MASs remain a limitation when the systems are large. Drawbacks such as the validating difficulty, the practicality of involving large stakeholder groups and the lack of generality are also quite obvious issues that are worthy of consideration (Liang et al., 2019; Osman, 2012; Son et al., 2015). Finally, data unavailability is a general problem that has been noted by many researchers in various fields, with impacts on both the accuracy and performance of agent-based simulation models.

Based on the collected publications, MAS applications at the macro level focus on exploring the behaviours of urban residents, addressing issues of policy implementation and emergency response. Therefore, integrating construction-domain knowledge in MAS applications is an essential concern for researchers. Further efforts can start with generating evolutionary MAS and computer-aided design techniques derived from AI research (Lv et al., 2021). Integrating big data from buildings with GIS may also facilitate the use of building information and the simulation of physical space; thus, agent-based models can become more accurate in reflecting the real world. MAS applications have evolved slowly but steadily during the past few decades, with a tendency towards the development of large-scale applications that are capable of supporting policy analysis and decision-making processes (Macal, 2016). Taking the uncertainty, complexity and dynamics of urban-related problems into consideration, issues such as the development of agents' self-learning and adaptive capacities could be further explored, which would be valuable to enhance cities' emergency responding abilities and providing information for policymakers (Pan et al., 2020b; Shou and Lai, 2011; Tah, 2005; Wang et al., 2020).

MAS applications at the micro level emphasise support for supply chain management and the improvement of project performance. Because a supply chain can significantly affect the performance of construction projects, the management of supply chain is crucial. Several studies concentrate on the bidding and tendering process of construction projects and apply case- or scenario-based studies to explore investment- and budget-related problems. Previous research explores the allocation of human and material resources and addresses issues in the context of negotiation and cooperation among multiple stakeholders. However, limited attention has been given to issues arising from the decision-making process in sustainable construction projects. For example, applying MASs in residential buildings fuelled by hybrid systems with renewable energy to reduce energy consumption and ensure acceptable comfort for residents (Calvaresi et al., 2021; Saba et al., 2017; Verma et al., 2020; Yin et al., 2020) could serve as a starting point for applying MASs to the sustainable construction.

7 Conclusions

MAS applications are recognised as among the most promising paradigms for conducting detailed investigations and providing reliable problem-solving methods, and such applications make it possible for researchers and practitioners to better understand complex systems from the perspective of construction management. In this paper, the applications at the macro and micro levels are summarised. At the macro-level, the use of MAS to deal with issues regarding the behaviours of urban residents and address policy implementation and emergency response situations are explored. While at the micro-level, the use of MASs to support the supply chain management and to improve project performance are identified, and the characteristics and working mechanisms of the MAS are analysed. Utilising MASs to support supply chain management focuses on three aspects, specifically, allocation of human and material resources, negotiation and cooperation among stakeholders, and the balance between investment and budget. Employing MASs to improve construction project performance concentrates on optimisation of design, enhancement of productivity and workers' safety performance. A framework for developing the agent-based model to address complicated problems from the perspective of construction management is proposed for researchers and practitioners to follow. The five steps begin with the problem statement, followed by multi-agent confirmation and agent-based model establishment, experimentation and model validation, and end up with the model application.

The MAS is a powerful tool that provides a bottom-up understanding of complex consequences from the perspective of construction management. However, the MAS still faces challenges at the implementation level, including but not limited to difficulties in data acquisition, model validation, and outcome assessment. In this instance, further study of these issues may begin with a focus on combining construction domain knowledge with MASs, making hybrid modelling more efficient and exploring how MASs can better support policy analysis and decision-making issues.

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