Establishment and Application of Multi-agent Simulation System Based on On-Site Construction Performers

B. D. Liu, B. Yang(✉), Yilong Han, J. Z. Xiao, and M. S. Dong

College of Civil Engineering, Tongji University, Shanghai 200092, China
yangbin@tongji.edu.cn

Abstract. Despite the literature on multiple decision agents in the construction process, questions regarding the on-site behaviour of construction performers and their interaction with the site remain unanswered. The study aims to simulate the construction process based on the behaviours of on-site construction performers. It first establishes a multi-dimensional simulation environment that includes construction procedures, work plane and component states. Then the Spatio-temporal attributes of the construction performs are encapsulated into the agents. And last, the interaction mechanism between the agents and the simulation environment is defined, that forming a multi-agent-based simulation system for the construction process. The proposed system is developed using Python code, which can be applied to simulate short-term construction process with agents modeling, environment modeling and agents' strategies et al. information imported, and a real case study is carried out through this way. The case study shows that the result of the established system has passed the verification of the traditional discrete event simulation result. And a construction strategy testing proves that this system can help managers to test and quantify the impact of different construction strategies so as to choose the most effective one to execute.

Keywords: Multi-agent-based simulation · Construction process · Discrete-event simulation · BIM

1 Introduction

The construction process is a complex progressing system consisting of various procedures in which experiential management weighs more than scientific deduction. To describe a construction process with a complex hierarchical level, a widely used way is to break it down into a series of small procedures, such as the work break down structure ("Framework for a Generic Work Breakdown Structure for Building Projects | Emerald Insight" n.d.), which continuously decomposes it into sub-processes with pre-sub relationships, and a task network, or rather, the Petri net (Sawimey 1997) is formed. To study the possible time and resources consumption of tasks in the network, the discrete-event simulation (DES) method is adopted (Dori and Borrmann 2012)(Benevolenskiy et al. 2012). However, it is a simplified deduction of the actual construction process in which

G. Geng et al. (Eds.): *Proceedings of The 17th East Asian-Pacific Conference on Structural Engineering and Construction, 2022*, LNCE 302, pp. 284–304, 2023.
https://doi.org/10.1007/978-981-19-7331-4_23

the interaction of construction crews and individuals would have a minimal impact on this evolution (Ben-Alon and Sacks, n.d.).

The multi-agent-based simulation is a powerful tool for studying the complex resource allocation in the concurrent construction procedures, which reorganizes the macro construction process in a buttom-up way, which insights into the complex system (Khodabandelu and Park 2021; Farshchian et al. 2017). However, current relevant studies are mainly focused on the large scale tasks such as the whole construction process of one floor (Ben-Alon and Sacks 2017), rather than the time-space behaviors of on-site actors when performing small scale-tasks, which is particularly important for on-site managers when managing short-term construction procedures. Without solving these problems, lean management is difficult to apply to on-site construction and can be combined with detailed construction data identified by emerging computer technologies. According to the motto of agent-based computational modeling: If you didn't grow it, you didn't explain its emergence (Epstein 1999). Therefore, a multi-agent system (MAS) that considers the detailed flow of construction resources (worker, materials and equipment) in the limited workspace is urgently needed to provide on-site managers with a reliable explanation and references of the entire construction process.

This paper propose a novel MAS based on construction actors for space-time deduction of the construction process in floor plane. It first establishes a multidimensional simulation environment that includes work procedures, sites, and component states, then summarizes the spatio-temporal attributes of the construction actor and encapsulates them into the construction agents. And last, the interaction mechanism between the agents and the simulation environment and between agents are defined, forming a multi-agent-based construction simulation that considers the triple effects of the process, material, and time-space. The proposed system is developed using Python code, which can be applied to simulate short-term construction process with agents modeling, environment modeling and agents' strategies et al. information imported, and a real case study is carried out through this way. Besides, the proposed MAS system has passed the verification of the traditional DES simulation method, whereas the MAS system can study more general emergence results through the adjustment of agent attributes.

Compared with the existing MAS research in construction, the novelty of this study lies in the agent modeling of the construction actor agents rather than the construction process, and the simulation scale is more detailed down to the procedures of the component. The practical contribution is the established MAS realizes the emergent of the macroscopic construction process from the basic flow of crews and materials, which provides a reliable tool to predict the impacts of construction measures for on-site managers, and can help managers to test and quantify the impact of different construction strategies so as to choose the most effective one to execute.

2 Reviews

2.1 Multi-agent Based Construction Simulation

Construction simulation is widely used to predict and validate the possible construction progress in an efficient approach (Halpin and Kueckmann 2002); and the MAS and DES are its main techniques (Zhang et al. 2011). MAS is a system modeling tool composed of a collection of entities with their characteristics, behavior rules, and interactions that enable the modeling of distinctive construction elements (Khodabandelu and Park 2021), which has been widely applied in constructions such as contractors bidding, planning and scheduling, equipment and labors analyze (Khodabandelu and Park 2021). The current MAS researches in construction mainly take the high-level construction procedures (Taghaddos et al. 2014), workflow (Hsieh and Lin 2015), the decision agents (Mostafavi et al. 2016), (sub)contractors (Kim and Paulson 2003), or projects (Farshchian et al. 2017) as agents, whose micro behaviors or rules are abstracted from real word and modeled as agent in system. For example, Ali et al. simulate the micro behaviors of state Departments of Transportation, private institutional investors, and the public in a multi-agent system for ex-ante analysis of financing policies (Mostafavi et al. 2016). In most existing systems, agents are defined as the bidders and the resources such as construction resources, financial resources, or construction opportunities are taken as the sellers. In this way, the simulation of the actual system is transformed into the auction between bidders and sellers. And the additional auctioneer agent who controls the auction process can be added to form a hierarchy agents system (Mostafavi et al. 2014).

Most of the current relevant studies do not consider the time-space behaviors of on-site actors when performing component-level tasks, which is particularly important for on-site managers when facing urgent short-term construction procedures. There is research that takes the crews as the agents to consider the space congestion caused by crew tasking in a work plane(Watkins et al. 2009). However, the congestion effect of agents' movement is not considered, and the other materials and equipment flow are ignored, which could also affect the time of the construction process and the congestion of the work plane.

Thus, there is a need for detailed agent simulation of the on-site construction actors and their interaction with materials and large equipment to study the time-space evolution of the short-term construction process.

2.2 The Time-Space Conflict or Congestion of Agents

To simulate the detailed component-level construction process, the behavior and interaction of on-site actors with limited construction space and resources should be considered. Watkins et al. noticed that labor efficiency could be treated as an emergent property resulting from individual and crew interactions in space (Watkins et al. 2009). They used agent-based modeling methods to simulate space congestion on a construction site, to explore the impacts of individual interactions on productivity and labor flow. However, this study did not account for congestion caused by agent movements. Although few studies have considered the spatiotemporal properties of agents in construction process simulations, other fields of research for studying the collision or blocking caused by agent movements that can be referenced. Kim et al. (2010) proposed a MAS based on traffic agents to simulate earthmoving operations where vehicle speed, distance from other vehicles, and decision-making of lanes change are considered to assess the impact of traffic congestion. However, it is not applicable in a crowded work-plane where agents are slow. The other example is a meshed work-plane that records the agents' positions and space occupation by girds. Li and Xu (2020) proposed a safety evacuation model that meshes the limited space and accommodates person agents in cells whose the state is either occupied or vacant. It brings such contradictory problems when studying the space-time congestion caused by agent movement, that if all the swept grids of an agent are taken as totally occupied in this time step, the space is obviously wasted. It also leads to how to simulate the congestion effects of soft constraints.

3 Multi-agents System Establishment Process

The purpose of the proposed MAS is to simulate the time-space occupancy and congestion evolution of the short-term construction process with the participation of multiple construction actors. The modeling process of this system is adopted from the process described in (Kim and Kim 2010). It first divides the construction process into actors, work plane environment (with materials located), and the procedures environment. Then defines the crews, equipment et al. construction actors as the agents, extracts their space-time attributes, and simulates their interactions with the environment or themselves from the actual process (Fig. 1). Besides, limited material is located at the work-plane and is replenished by agents who transport materials from the site. In this way, the five elements of man, machine, material, method, and space in the construction are both considered in the system simulation. They work together in the system to realize the space-time deduction of the construction in the work plane.

4 Mas Based on the Construction Actors

This study defines agents as on-site construction actors who have specific target tasks and are considered whole when moving or tasking. A novel multi-agent system based on the on-site actors is proposed with three parts, the agents, work-plane environment, and construction procedures environment (Fig. 2).

4.1 Construction Procedures Environment

The construction process can be decomposed and organized into a series of tasks with pre-success relationships. It is important to determine whether the decomposed tasks are executed exactly by one crew agent, especially construction tasks that often vary in size. This problem was resolved in our previous study (Yang et al. 2021), which established a flexible WBS structure for tasks organization that makes the tasks or multi-component tasks executable by one crew (allowing the assistance of public equipment). Thus, the organized tasks in (Yang et al. 2021) can be directly imported into the construction procedures environment of this system, which is the flow of tasks in the four task pools according to their attributes and the current system state (Fig. 3). The {task_wait} contains the tasks whose predecessors not finished; {task_quene} contains the tasks whose predecessors are finished; {task_on} contains the tasks under execution; {task_end} contains the finished tasks. Besides, the organized tasks contain the following attributes that will be passed for agents **for time-space occupation mechanism**: the involved components (or elements) of the task t_{ele}, the position of the task t_{pos}, which is the center of the involved components, the tasking scope t_{sco}, represented as the component enclosing rectangle with working distance and safety distance extended (Fig. 4).

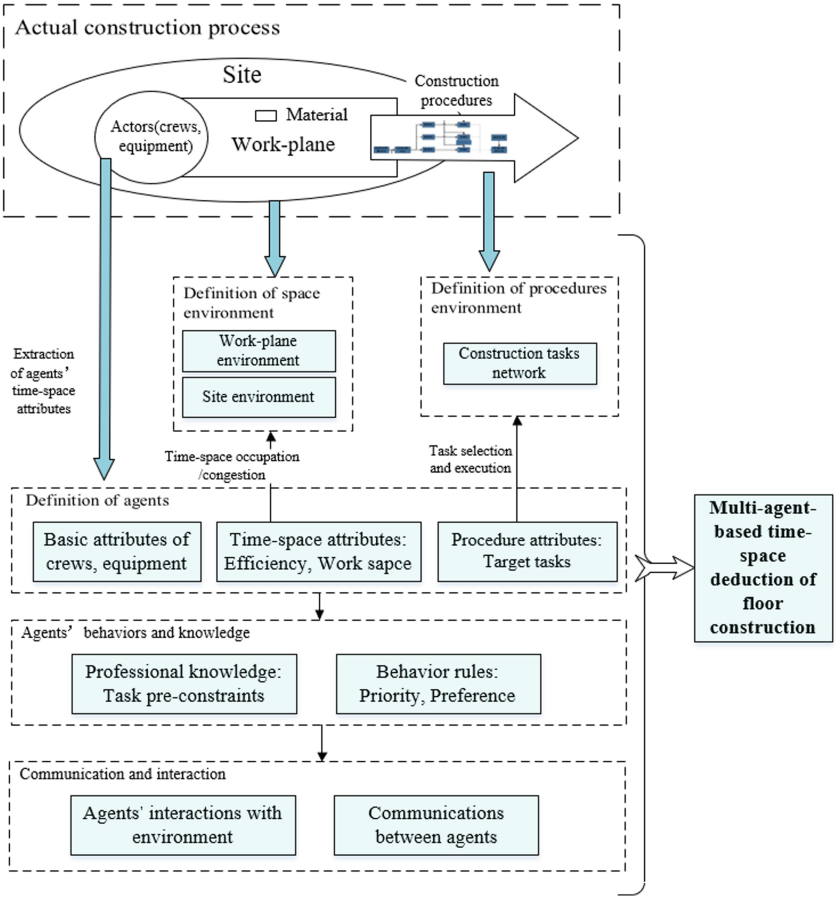

Fig. 1. The establishing process of this MAS system

4.2 Work Plane Environment

The work plane is the main container of agents, materials, and construction measurements Two kinds of constraints can be classified when agents behave. The first are the hard constraints that refuse the invasion of agents, whose geometric information mainly comes from the BIM model. The second are the soft constraints that hamper agents moving, such as temporary measurements, materials storages et al. To study the congestion effects caused by various factors on agent movements, the path blocks are proposed to consist of one of the work plane environments.

4.2.1 Hard Constraints

Since the vertical components have structures such as survey lines and protruding steel bars before construction, they and openings can be regarded as hard constraints at the beginning. Hard constraint geometries can be imported into the system through the BIM

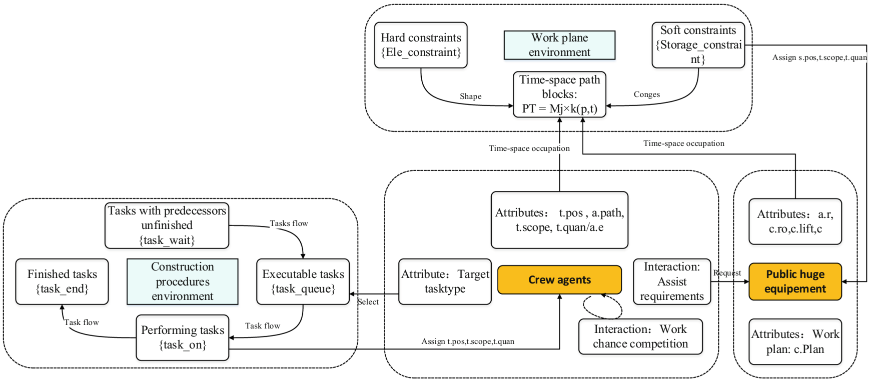

Fig. 2. The proposed of MAS consists of three parts

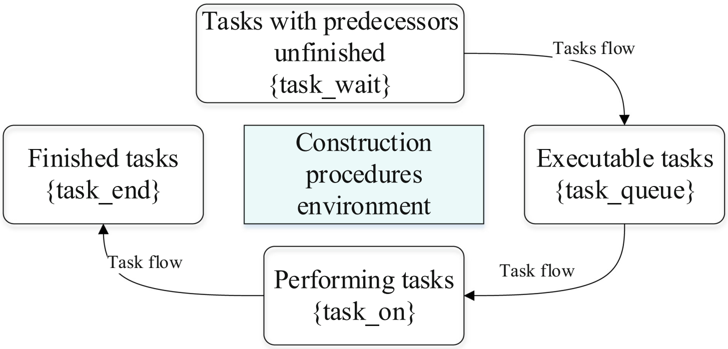

Fig. 3. The construction procedures environment of this system

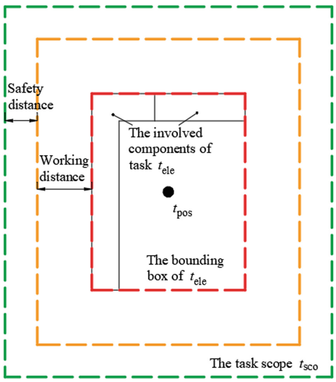

Fig. 4. The diagram of task's geometric attributes

model as $\{C_{hard}\}$. The BIM model will continue to provide the system with information about components, such as quantity, type, etc.

4.2.2 Soft Constraints

There are always types of things in the work plane as soft constraints to hamper the agents' movements. The soft constraint C_{soft} is defined as geometry with a congestion index I_C in the work plane in this system. I_C is used to describe the congestion degree of the soft constraint in a unit area. 0 represents no congestion, and 1 wholly blocked or hard constraint. Three types of soft constraints and their congestion indices are defined: the material storage are $C^{m}{}_{soft}$ and $I^{m}{}_{C}$; the task scope are $C^{t}{}_{soft}$ and $I^{t}{}_{C}$; the material storage are $C^{m}{}_{soft}$ and $I^{m}{}_{C}$; and the temporary measurement are $C^{e}{}_{soft}$ and $I^{e}{}_{C}$. Different types of soft constraints have different ways to determine their I_C value. For example, for a material yard, its $I^{m}{}_{C}$ value depends on the ratio of its current reserves to its area, and the $I^{m}{}_{C}$ value can be linearly related to the reserves, that is, when the reserves are 0, $I^{m}{}_{C} = 0$, and when the reserve exceeds a threshold its $I^{m}{}_{C}$ is always = 1. The practical meaning is that the highly stacked storage completely hinders the agent's movement. The $I^{t}{}_{C}$ of the task scope is determined by the works number and activity level of the crew performing the task.

4.2.3 Path Blocks

This study proposes the path blocks to simulate the movement congestion for agents based on the following assumptions:

1. To consider the security and management of the flow of workers and equipment, the movement of crews follows fixed paths in the work plane which can be concreted in the simulation;
2. Any overlapping parts of the constraints and path block will cause blocking effects, but because the flexibility of the agent, its impact can be evenly distributed over the blocks;
3. The congestion caused by the agent's movement in a time step can be allocated to the passed blocks in proportion to the time the agent takes to pass the block. The actual meaning is that the longer the agent spends in the block, the greater the congestion impact it will cause.

The path blocks is the discretization of the path area like Fig. 5. And each path block P_i will get an initial congestion matrix to record the current or future congestion degree of this block:

$$P_i\_G = [\text{steps}]_{\text{m}\times 1} \times [0] \tag{1}$$

where [steps] is an m × 1 column vector, representing the time steps of the system, which can be extended.

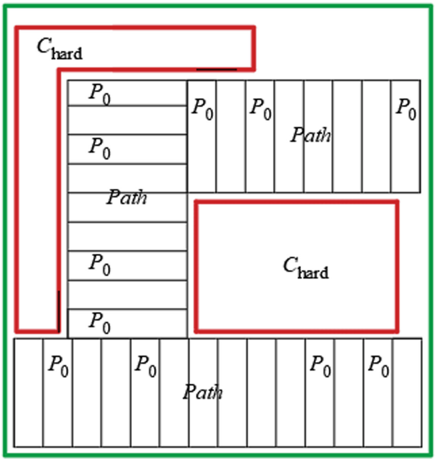

Fig. 5. The diagram of path blocks

4.3 Construction Actor Agents

This study defines construction actors as the crews or large equipment that constantly serve specific construction tasks are taken as the agents, and determines their attributes and rules. There are mainly two types of actor agents in this system. The first is the crew agent, which comprising one or more workers and a carried equipment, and the large public equipment that serves multiple tasks and crews, such as tower cranes and elevators.

4.3.1 Crew Agent

Each crew agent a is responsible for a fixed type of task a_{type} and moves around the work plane to the task location for construction. To simulate the time-space actions of crew agents in the construction process, the attributes of agent movement width in path a_{wid}, agent's velocity a_{v}, the agent's work efficiency a_{e}, and the agent's tasking scope t_{scope} should be considerate. Among them, a_{wid} is based on crew size and the required safety distance when moving, and the attributes about the task are passed from the target task to the agent.

4.3.2 Public Equipment Agent

The large-scale equipment in construction may have its operation logic and can work for various task types. The most important public equipment in the building construction is the tower crane, whose execution time has been well defined in research (Wu et al. 2020): One lifting time of tower crane is composed by lifting time T_{lift}, loading time T_l, and unloading time T_u three parts. T_l and T_u are the given time, and T_{lift} needs to be calculated according to the Eqs. 2–9 (Wu et al. 2020).

With the given tower crane k with position ($\text{TC}^k{}_x$, $\text{TC}^k{}_y$, $\text{TC}^k{}_z$), the hop position $H = (H_x, H_y, H_z)$ and the target position $D = (D_x, D_y, D_z)$, one lift time of tower crane k

is $T^k{}_{\text{lift}}(H, D)$ that can be calculated:

$$T^k_{\text{lift}}(H, D) = \max(T^k_v, T^k_h) + \beta \times \min(T^k_v, T^k_h) \tag{2}$$

$$T^k_v = \frac{|D_z - H_z|}{V^k_v} \tag{3}$$

$$T^k_h = \max(T^k_\alpha, T^k_\omega) + \alpha \times \min(T^k_\alpha, T^k_\omega) \tag{4}$$

$$T^k_\alpha = \frac{|\rho(D) - \rho(H)|}{V^k_\alpha} \tag{5}$$

$$T^k_\omega = \frac{1}{V^k_\omega} \times \arccos(\frac{\rho(D)^2 + \rho(H)^2 - l^2}{2\rho(D)\rho(H)}) \tag{6}$$

$$\rho(H) = \sqrt{(TC^k_x - H_x)^2 + (TC^k_y - H_y)^2} \tag{7}$$

$$\rho(D) = \sqrt{(D_x - TC^k_x)^2 + (D_y - TC^k_y)^2} \tag{8}$$

$$l = \sqrt{(D_x - H_x)^2 + (D_y - H_y)^2} \tag{9}$$

$T^k{}_v$ and $T^k{}_h$ mean horizontal and vertical movement time of the tower crane hook, β represents the coordination degree of the hook movement in the horizontal and vertical planes between 0 and 1, which assume to be 0.1 (Younes and Marzouk 2018); T^k_α the radial movement time, T^k_ω the slewing movement time; V^k_α the radial velocity of the trolley, V^k_ω the slewing velocity of the jib; α represents the coordination degree of the hook movement in radial and slewing directions in the horizontal plane between 0 and 1, which assume to be 0.25. The detailed description of the Eqs. 12–9 can be found in (Younes and Marzouk 2018).

By identifying the operating status of the tower crane in the actual construction video, our team obtained the basic data of the tower crane operation: $V^k_\alpha = 667$ mm/s, $V^k_\omega = 0.172$ rad/s, $T_u = 78.23$ s, $T_l = 73.57$ s. Besides, benefit from the continuity of the simulation of this system, the tower cane with a new mission retains its empty state of the previous time step; thus, the mission time of the tower cane can be calculated without distinguishing the empty or full load states:

With the given tower crane k, the hop position $S = (H_\text{x}, H_\text{y}, H_\text{z})$, the target upload position $D1 = (D1_\text{x}, D1_\text{y}, D1_\text{z})$, and the target unload position $D2 = (D2_\text{x}, D2_\text{y}, D2_\text{z})$, the action time $T^k{}_{\text{act}}$ is:

$$\text{T}^k_{\text{act}} = \text{T}^k_{\text{lift}}(H, D1) + \text{T}^k_{\text{lift}}(D1, D2) + \text{T}_u + \text{T}_l \tag{10}$$

Since the tower crane is not on the same plane as the floor, its space occupation will only conflict with other tower cranes. And the time occupancy will cause the time and space occupation of the work plane through the interaction with the agent.

The task targets performed by the tower crane come from the interactive requests of crew agents, mainly for task assistance, such as the hoisting of prefabricated components and the hoisting of materials.

4.4 Time-Space Conflict and Congestion Mechanism

The congestion in the work plan only considers the congestion impact on time-space path blocks, and only the task execution conflict. The following Time-space conflict and congestion mechanisms are defined:

Task scope conflict mechanism: This system rules that the time and space occupied by different tasks must not conflict. For any task t that is about to start at the current step, its task's space occupancy t_{sco} must not conflict with any performing task in {Task_on} or agents' registered tasks.

Agents' movements congestion on path blocks: The time for the agent to pass through each block is determined by its moving speed, the block's width, and the current congestion value of the block. Since it is assumed that the blocking effect caused by the agent's movement will be proportional to the passing time, assuming that the agent is stationary for a one-time step (*S* seconds), it will completely block its occupied area. When it takes *s* seconds to pass through a block, its congestion to this block is s/S compared to its inactivity.

Tasks scopes congestion on path blocks: The overlapping area of the task scope and the path block is the task's contribution to the path congestion during task performing.

Temporary storages congestion on path blocks: Since agents are less hampered when passing the storage with fewer reserves. The contribution of the storage to the path's congestion depends on its area and its current reserves.

4.5 The Actions of Crew Agents

4.5.1 Agents Targets and Paths

Assume agent *a* gets an alternative target, the path between the agent's position and the target can be found by the **exhaustive method**: The agent first enter into the closed path blocks *Pi* and keep moving into the following block to get closer to the target, until arriving the target's closet block. The passing of the agent can't make any path blocks completely blocked in the agent's path.

The agent's potential targets are determined by its internal knowledge, such as task type, task pools statues, and workspace statues:

(1) If an agent needs to acquire materials, its target is the corresponding material storage.
(2) else, the agent chose a task from {task_quene} as its predetermined target tasks, which needs to satisfy three constraints:

   a. must be the same type with agent's task type;
   b. not conflicts with any other tasks in {task_on} and targeted tasks by agents;
   c. The path to the target is fluent.

4.5.2 Agents' Actions and Pathing

The agent has two main actions; one is to perform the task, which occurs around the target components. In this system, the task is progressively advanced over time steps based on the agent's efficiency, step length, and probability distribution until its reaches

100% completed. Then the agent becomes idle, removing the task target and freeing the task scope. Another primary action is acquiring material, which occurs near the material yard and takes a certain time for the agent to acquire. When the assistance of the tower crane is required for these two types of actions, it takes additional time for the tower crane to lift the component or material, which Eq.x can calculate. The tower crane will also be occupied when assisting the task that the occupied time is determined by the assistant workload or work steps and the crew agent's efficiency.

The agent must reach the corresponding location through the path before performing the task or material acquisition action. In addition, the agent will also participate in the competitive action of determining the target and the action of initiating a request to the tower crane.

4.5.3 Agents Decision-Making Framework

The agent will make a series of decisions and behaviors according to the current state of the system and its state, affect and change the internal properties of the agent and perform corresponding actions. The actions will further change the system state.

At the beginning of each step, the agents who have determined their target may have reached the target's position through the path. Identify the status of these agents to see if it is true, then identify whether the agent needs the assistance of tower crane. If there is no need, the agent starts its action (**acquire materials** or **start task**) in the target. The detailed decision-making process of the crew agent is shown in Fig. 6.

4.6 Agents' Interaction

The purpose of agent interaction is to solve the problem of insufficient space or public equipment caused by concurrent actions of multiple agents. The interaction between crew agents is mainly related the competition over limited space or task opportunities. While the interaction between the crew and equipment agents is primarily related the crew's request for equipment's assistance.

4.6.1 Interaction Between Crew Agent and Equipment Agent

When the crew agent needs the assistance from the tower crane, it sends a request to the tower crane which is stored in the crane's plan. There are two types of request: task assistance and materials hoist. If the request is material hoist, the material type and material quantity (optional) need to be declared in request. The tower crane can obtain the site location of the material from the internal knowledge of the system and the storage location in the work plane according to the material type. For task assistance request, the task type t_{type}, the task location t_{pos}, and the assistance workload t_{quan} need to be declared in request, the assist time steps of crane is calculated by the assisting workload and agent work efficiency: $t_{\text{quan}} / e_{\text{a}}$, that the total steps of crane spend on task assistance is $T_{\text{assis}} = T_{\text{lift}} + t_{\text{quan}} / e_{\text{a}}$. In each step, after all crews send the requests, the tower crane selects the highest priority request in its plan to assist when it is idle. Generally, the priority of material lifting requests is higher than that of task assistance request.

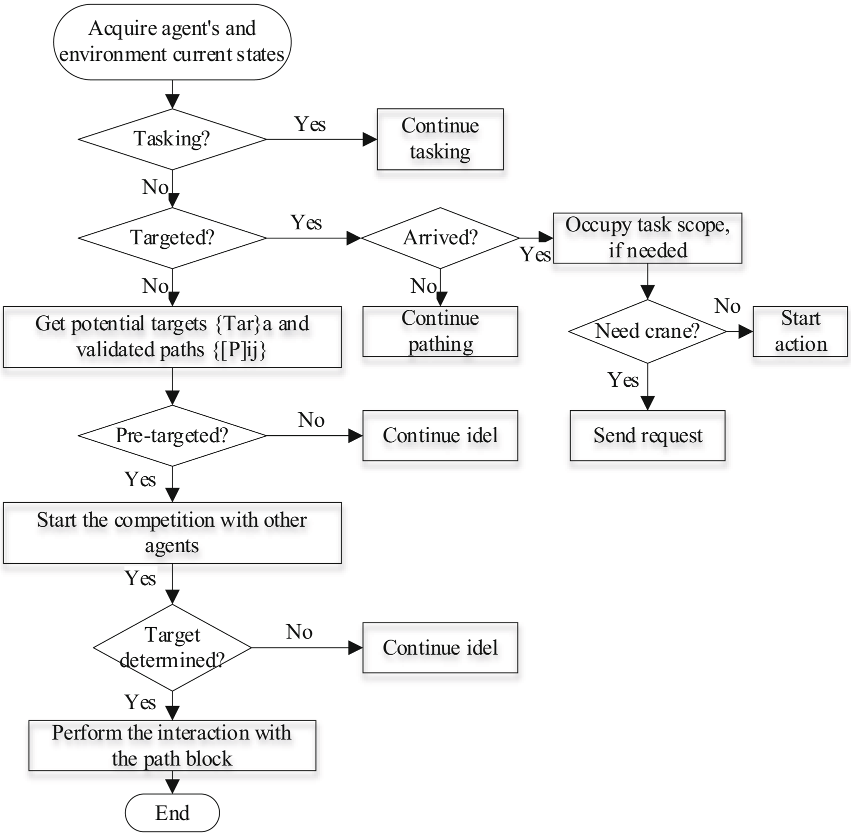

Fig. 6. The crew agent decision-making process

4.6.2 Interaction Between Crew Agents

At the beginning of the time step, all idle agents try to predetermine their targets according to the "Agent's Target" and verify their paths that are passible. Owing to limited space and congestion paths, only some of the agents can determine its target and path at each step. The that agent determines its target earlier can preferentially register the corresponding spatiotemporal behavior, affecting the congestion matrix of the path block and the available space for tasking. For a predetermined target, its priority is affected by the target type, the number of its successor tasks, the length of paths, and the degree of target preparation.

Each time, only the target with the highest score can be determined, and the agent begins its path to it, affecting the space-time congestion matrix of the path blocks and registering the task scope for tasking. After updating the system's space-time conflict and congestion environment, re-validate other agents' targets and paths that targets not validated are removed.

4.7 The Development of the Proposed MAS

The python code is used to develop the proposed system, which is widely used in developing related MAS systems that provide sufficient tools and references for the development of this system.

The developed system contains a User Interaction Module (UI), where the user needs to set basic simulation parameters such as the actual duration of the time step, the maximum time step, and so on. In this module, users can add a temporary storage yard and specify the location, range, and initial reserve, set the number of agents used in the simulation, specify the initial position and status of the agents, and adjust spatiotemporal attributes of the agent instances.

The main body of the program realizes the interactions between the agents and the environment and agents through Python code and driven by the discrete-time steps. The general execution processes are shown in Fig. 7.

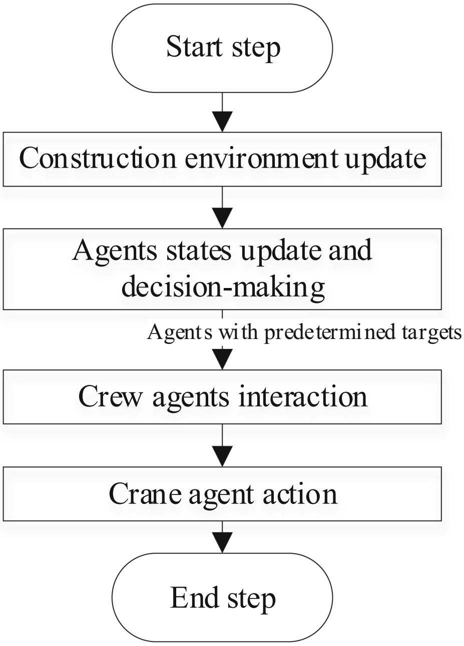

Fig. 7. The execution process in each step of this system

1. Environment status update. Tasks stream between the four task pools according to their start time, end time, system's current time step and completion status of the predecessors that updates the procedures environment. The finished tasks release the occupied task scope that updates the work plane environment.
2. Agents' decisions and actions. Agents make a series of decisions and actions described in "Agents decision-making framework", whose actions continuously affect and change the work plane environment.

3. Crew agent's competition and action.
4. Crane agent action.
5. End step: Mask supplementary records for the agents that have no recorded state at this time step, whose state is supplemented to idle, and the position remains unchanged.

5 Case Study

A prefabricated structure in Shanghai was considered as a case study. To ensure the consistency of the work plane in the simulation, this case only involves the construction process of the vertical components of this structure, including 28 components in three types of prefabricated walls/columns, cast-in-place walls, and cast-in-place column. And the construction contains 4 types of tasks whose attributes are summarized in Table 1.

Table 1. The task types in this case study

Task Name	Abbreviation	Agents	Work distance (mm)	Safe distance (mm)	Material storage
PC wall Hoisting and Installation	PC	TC, PCW	1500	1000	Struts
Grouting	G	PW	800	300	Mortar
Reinforceing	R	RW	1200	300	Rebars
Formworking	F	F&SW	1500	500	Templates

5.1 The MAS of This Case

5.1.1 The Construction Procedures Environment

Based on the previous research, the construction BIM model of this case was established: The existing building BIM model was used to generate process patterns at component levels, and the required multi-component tasks and tasks' pre-successor relationships to form the tasks of the construction process, which is combined with the original BIM model to form a construction BIM model. Information such as task predecessors, task-related components, associated component locations, and associated component engineering quantities in the construction BIM model were extracted and imported into the system as task attributes. According to the task' attributes and agent' actions, the program drives tasks to flow in different task pools to form the process environment.

5.1.2 The Work Plane Environment

The work plane environment of this system is composed of hard constraints, soft constraints and path blocks. In this case, the geometric information of the hard constraints, such as the working face shape and components, is obtained from the BIM model. Soft constraint information such as material yard and temporary measures on the working face can be obtained from the construction BIM model or specified by the user. For example, data such as the maximum storage yard, storage range, etc., or accompanying tasks for temporary measures. In this case, two storage yards are designated on the working face, namely the rebar storage, the Struts storage, the Mortar storage, and the template storage, the positions and scopes of which are shown in Fig. 8 also shows the path block used in this case.

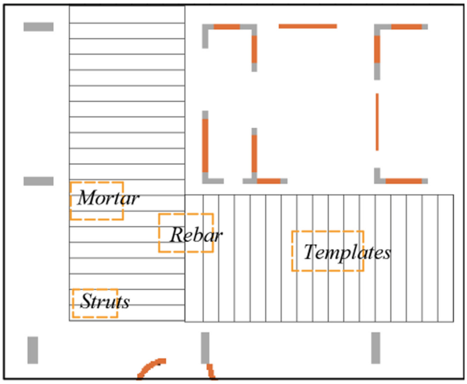

Fig. 8. The layout of the work plane environment

5.1.3 Agents of Construction Actors

To perform the tasks of this case, four types of crews and one tower crane were used. Crew agents and their temporal-spatial attributes are summarized in the following Table 2, which data were obtained from actual engineering. The tower crane agent uses the parameters in the section "*Public equipment agent*".

Table 2. The agents applied in the case study

Agents	Work efficient /Duration	Movements width (mm)	Velocity (mm/s)
PCC	25 min	2000	6000
GC	9 min	1000	9000
RC	0.035 m^3/min	900	10000
FC	0.56 m^2/min	1300	7000

5.1.4 User Settings in the Main Body of the Program

In this case, the simulation settings are shown below.

Initial task environment status: All tasks are not started;

Initial working face environment: Three temporary storage yards are placed, the reserves of all temporary storage yards are 0, and the space-time blockage of all path areas is [0];

Quantity setting of agents: reinforcement crews (RC) 2, PCs hoisting and install crew (PCC) 1, mortar grouting crew (MC) 1, formwork crew (FC) 2. Each agent is generated at the beginning of the simulation, inherits all the properties of the same type of agent in the program agent module, and is assigned an initial spatiotemporal log, which records all the historical and future actions of the agent. At the same time, the unique feature of this program is that the generated agent will not be recycled during the simulation process, which allows the user to trace all the agent's actions through the agent for easy analysis.

Simulation drive (other) setting: the set time step length is 10s in reality, then the team agent moves about 6–11m per step, and the tower crane agent rotates about 98° per step.

5.2 Simulation Results and the Comparison with DES

Using the above settings to execute the developed MAS program, the simulation results of the construction process can be obtained and exhibited as the Gantt chart of each agent (Fig. 9). Which distinguishes three types of actions: idle (gray), move (yellow), perform a task (red). The Gantt chart reflects the participation of various agents on the work plane during the construction process, indicating that the proposed system successfully simulates the macro construction process from the basic agent modeling.

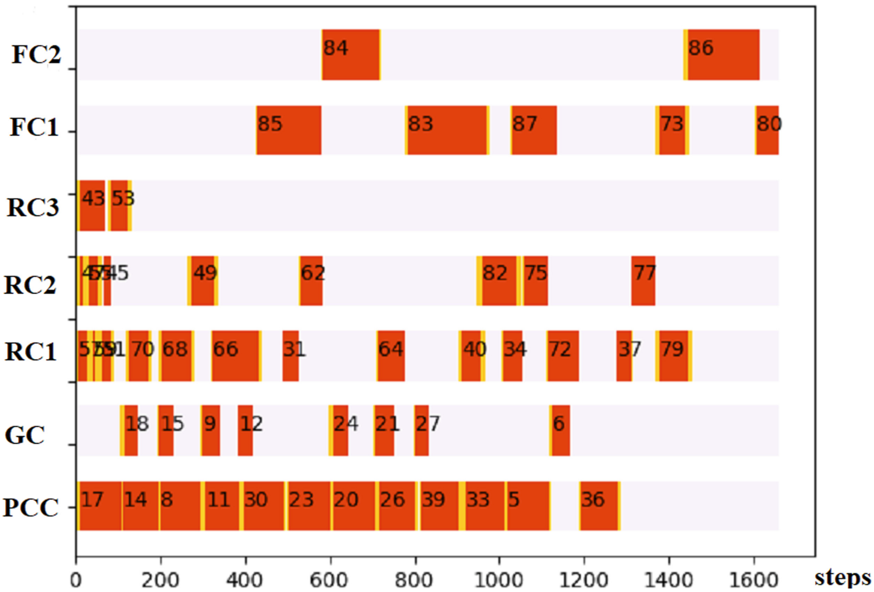

Fig. 9. The simulation results are shown in the agents Gantt chart

To verify the reliability of the simulation result, it is compared with the result of the DES method. DES results represent a good verification tool for agent-based models that the nature of DES provides an accurate flow of resources, which allows for verifying the quantitative aspects of agent-based models(Jabri and Zayed 2017). There are several examples in the literature on the verification of ABMS outputs using DES results [6], [10]. In this case, the simulation object of the DES method is the task network of the case; each task consumes the same resources and takes the same probability time as this MAS, while does not consider the flow of resources (workers, equipment, and materials). The comparison between the DES simulation and the proposed MAS simulation is shown in Fig. 10, which shows that the proposed MAS takes more time to complete all tasks than the DES simulation. The reason is that this system considers the agent's action and the related resource flow before the task start.

By re-setting the agent and environment parameters of the system to make the moving speed of the agent extremely high, the initial material reserves of the site extremely large, and the moving volume of the agent to be extremely small, and re-run the proposed system to get a result, which compares with the DES results in Fig. 11. It shows that in this specific condition, the simulation results of this system have a very high consistency with traditional DES simulations, indicating that the system is verified with the traditional simulation method.

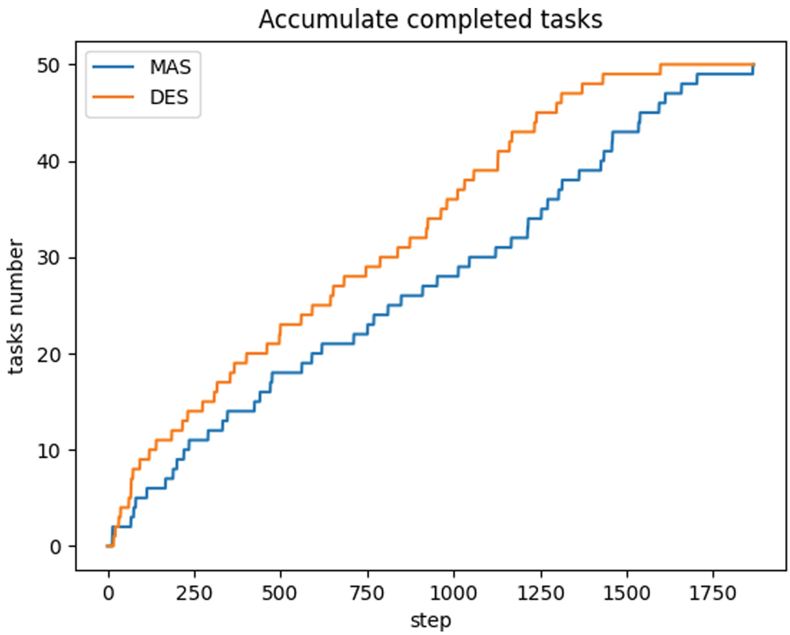

Fig. 10. The comparison of this MAS and traditional DES method in normal parameter

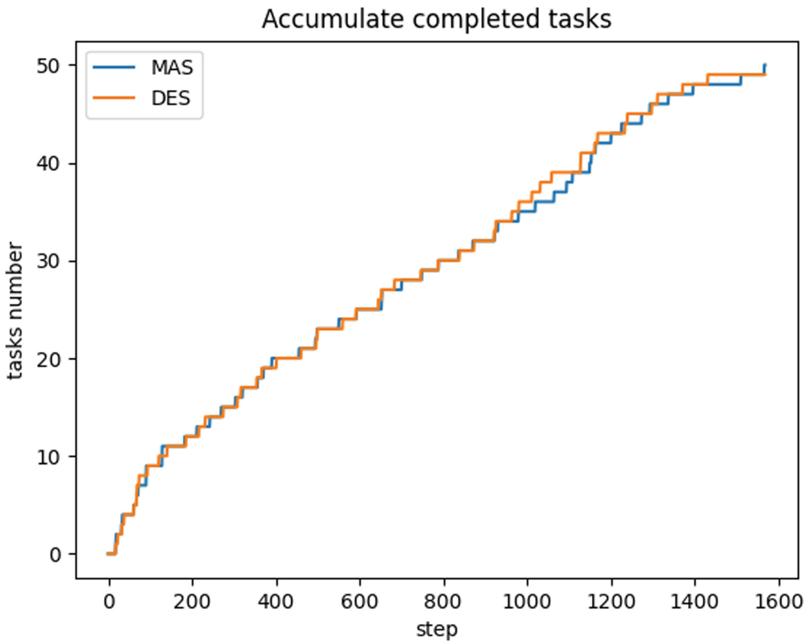

Fig. 11. The comparison of this MAS and traditional DES method in the specific condition

5.3 Construction Strategy Application Experiment and Result Analysis

To verify whether the established system can help managers test different construction strategies and understand the macro impact caused by them, the most commonly used construction strategy in practice is applied in this case, that is, changing the number of participants (crews) to test the system's performance in different situations. The variable controlled in this experiment is the usage of rebar crews in 1 (case1, blue line), 2 (case2, orange line), 3 (case3, green line), and 4 (case4, red line) are tested (Fig. 12). It can be seen from the figure that the increase in steel bar teams accelerates the overall construction process, while the more the crews invested, the smaller the acceleration effect. It is in line with engineering experience that shows the proposed system successfully emergent the micro construction phenomenon from the adjustment of agents.

6 Conclusion

The current construction-related MAS simulations lack consideration for the construction actors' movement on the short-term limited working surface. This paper proposes a MAS based on the on-site construction actors, defines the agent's spatiotemporal attributes, and further establishes the agent's operation and interaction rules between agents and between agents and the environment. The proposed system is developed using Python code and verified with a real-life case of the standard floor's construction of a prefabricated building in Shanghai. Besides, the comparison with the traditional

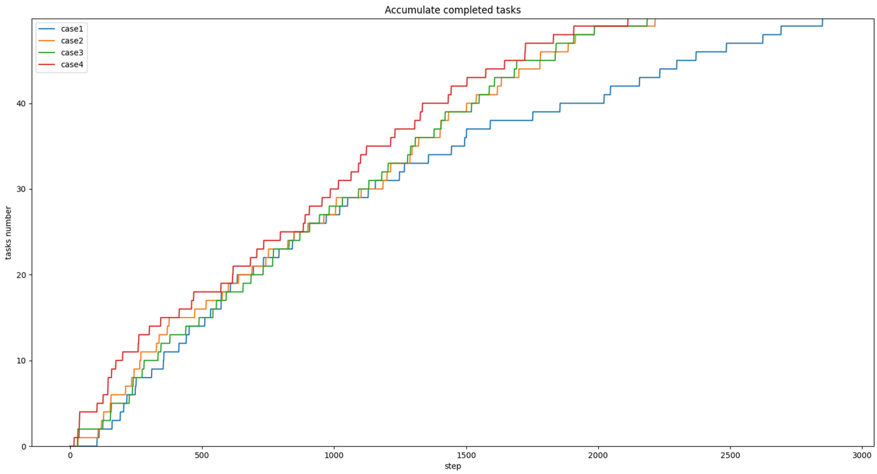

Fig. 12. The simulation results of the four strategies

DES method and the experiment of different construction strategies are implemented. And the following conclusions can be drawn:

1. The program can record the action history of different agents and visualize it for the construction managers to read and understand intuitively.
2. In specific cases, the result from the developed system is highly consistent with the result from the traditional DES method in this case, which means that this system is compatible with DES in task network simulation and resource usage, and verifies the effectiveness of this system;
3. The simulation results of the system for different numbers of crews are consistent with the engineering experience, proving that the strategies applied on agents impact the macro construction process.

The main contribution of this paper to related research fields is that it proposes a novel perspective for multi-agent modeling of the construction process. The simulation process can be more detailed based on the construction actor agents, and the measurements and preparations for tasks execution can be considered from the basic agents' actions, which helps to emergent the macroscopic construction process from the basic flow of crews and materials. In practice, the proposed system can show managers a more detailed agent action status to help them understand the macro construction process and quantify the impact of different construction strategies on the overall process.

A future of this system is to study the optimization method in the agents. Test the construction strategy about the usage of space in the work plane. For example, let the agent choose the task with a low degree of path congestion while with more performing tasks around, it is to avoid complete congestion of the path and free up contiguous non-task areas for the work plane as much as possible.

Acknowledgments. The study has been supported by the National Key R&D Program of China (Grant No. 2020YFD11004045).

References

Ben-Alon, L., Sacks, R.: Simulating the behavior of trade crews in construction using agents and building information modeling. Autom. Constr. **74**, 12–27 (2017). https://doi.org/10.1016/j.autcon.2016.11.002

Ben-Alon, L., Sacks, R.: Simulating and Vizualising Emergent Production in Construction (Epic) Using Agents and BIM 10 (n.d.)

Benevolenskiy, A., Roos, K., Katranuschkov, P., Scherer, R.J.: Construction processes configuration using process patterns. Adv. Eng. Inform. **26**(4), 727–736 (2012). https://doi.org/10.1016/j.aei.2012.04.003

Dori, G., Borrmann, A.: Determination of float time for individual construction tasks using constraint-based discrete-event simulation. In: Proceedings of the 2012 Winter Simulation Conference (WSC), pp. 1–12 (2012). https://doi.org/10.1109/WSC.2012.6465193

Epstein, J.M.: Agent-based computational models and generative social science. Complexity **4**(5), 41–60 (1999). https://doi.org/10.1002/(SICI)1099-0526(199905/06)4:5%3c41::AID-CPLX9%3e3.0.CO;2-F

Farshchian, M.M., Heravi, G., AbouRizk, S.: Optimizing the owner's scenarios for budget allocation in a portfolio of projects using agent-based simulation. J. Constr. Eng. Manag. **143**(7), 04017022 (2017). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001315

Framework for a Generic Work Breakdown Structure for Building Projects | Emerald Insight. (n.d.) Accessed 24 Feb 2022. https://www.emerald.com/insight/content/doi/10.1108/14714170910995930/full/html

Halpin, D.W., Kueckmann, M.: Lean construction and simulation. In: Proceedings of the Winter Simulation Conference, vol. 2, pp. 1697–1703 (2002). https://doi.org/10.1109/WSC.2002.1166453

Hsieh, F.-S., Lin, J.-B.: Project scheduling based on multi-agent systems. J. Adv. Manage. Sci. 211–218 (2015). https://doi.org/10.12720/joams.3.3.211-218

Jabri, A., Zayed, T.: Agent-based modeling and simulation of earthmoving operations. Autom. Constr. **81**, 210–223 (2017). https://doi.org/10.1016/j.autcon.2017.06.017

Khodabandelu, A., Park, J.: Agent-based modeling and simulation in construction. Autom. Constr. **131**, 103882 (2021). https://doi.org/10.1016/j.autcon.2021.103882

Kim, K., Paulson Jr, B.C.: Multi-agent distributed coordination of project schedule changes. Comput.-Aided Civ. Infrastructure Eng. **18**(6), 412–425 (2003). https://doi.org/10.1111/1467-8667.00327

Kim, K., Kim, K.J.: Multi-agent-based simulation system for construction operations with congested flows. Autom. Constr. **19**(7), 867–874 (2010). https://doi.org/10.1016/j.autcon.2010.05.005

Li, Z., Xu (Ato), W.: Pedestrian evacuation within limited-space buildings based on different exit design schemes. Safety Sci. **124**, 104575 (2020). https://doi.org/10.1016/j.ssci.2019.104575

Mostafavi, A., Abraham, D., DeLaurentis, D.: Ex-ante policy analysis in civil infrastructure systems. J. Comput. Civ. Eng. **28**(5), A4014006 (2014). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000350

Mostafavi, A., Abraham, D., DeLaurentis, D., Sinfield, J., Kandil, A., Queiroz, C.: Agent-based simulation model for assessment of financing scenarios in highway transportation infrastructure systems. J. Comput. Civ. Eng. **30**(2), 04015012 (2016). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000482

Sawimey, A.: Petri net based simulation of construction schedules. In: Winter Simulation Conference Proceedings, pp. 1111–1118 (1997). https://doi.org/10.1109/WSC.1997.640998

Taghaddos, H., Hermann, U., AbouRizk, S., Mohamed, Y.: Simulation-based multiagent approach for scheduling modular construction. J. Comput. Civ. Eng. **28**(2), 263–274 (2014). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000262

Watkins, M., Mukherjee, A., Onder, N., Mattila, K.: Using agent-based modeling to study construction labor productivity as an emergent property of individual and crew interactions. J. Constr. Eng. Manag. **135**(7), 657–667 (2009). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000022

Wu, K., de Soto, B.G., Zhang, F.: Spatio-temporal planning for tower cranes in construction projects with simulated annealing. Autom. Constr. **111**, 103060 (2020). https://doi.org/10.1016/j.autcon.2019.103060

Yang, B., Liu, B., Xiao, J., Zhang, B., Wang, Z., Dong, M.: A Novel construction scheduling framework for a mixed construction process of precast components and cast-in-place parts in prefabricated buildings. J. Build. Eng. **43**, 103181 (2021). https://doi.org/10.1016/j.jobe.2021.103181

Younes, A., Marzouk, M.: Tower cranes layout planning using agent-based simulation considering activity conflicts. Autom. Constr. **93**, 348–360 (2018). https://doi.org/10.1016/j.autcon.2018.05.030

Zhang, B., Chan, W.K., Ukkusuri, S.V.: Agent-based discrete-event hybrid space modeling approach for transportation evacuation simulation. In: Proceedings of the 2011 Winter Simulation Conference (WSC), pp. 199–209 (2011). https://doi.org/10.1109/WSC.2011.6147751