Spatio-Temporal Planning Simulation of Temporary Elevators in Construction Using a Game Engine

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Abstract –

Designing a reasonable and efficient transportation system of temporary elevators from the perspective of spatio-temporal planning is beneficial for the successful completion of construction projects. Specifically, the determination of the service date and floor of temporary elevators and the consideration of the limited availability of time and space should be taken seriously. The spatio-temporal planning of temporary elevators puts forward higher requirements for the display of planning solutions due to the complexity considering both time and space. However, current display ways are generally abstract, low-dimensional, and static, and even when the 4D model is adopted, the display effect of spatio-temporal planning solutions is still limited. This research presents a spatio-temporal planning simulation of temporary elevators in construction using a game engine to address those challenges. The workflow of the spatio-temporal planning simulation, divided into configuration and operation planning, consists of three steps: 1) import data into the game engine platform, 2) generate the spatio-temporal planning simulation scheme, and 3) conduct the spatio-temporal planning simulation. The results of the experimental test show that the presented spatio-temporal planning simulation way is intuitive and convenient, various planning elements are clearly shown, and corresponding planning information is efficiently conveyed, which can effectively enhance the display effect of spatio-temporal planning solutions.

Keywords –

Spatio-temporal planning; Temporary elevator; BIM; Game engine; Virtual reality

1 Introduction

The organization and control of construction activities taking the use of time and space into account separately have existed for many years [1][2][3]. It becomes static or plane planning when the use of time or space is ignored. Such separations are likely to cause potential time or space conflicts of construction activities, leading to various challenges such as safety, quality, delivery, and cost [3][4]. For those reasons, the organization and control of construction activities from the perspective of the use of both time and space, namely spatio-temporal planning, has been gradually valued in recent years because it effectively integrates both of them [5][6][7].

The temporary elevator, used to transport workers and small and medium-sized materials, is one of the most common transportation equipment in construction projects [8]. It significantly impacts safety risk, production productivity, and capital investment [9][10]. Temporary elevator planning, namely designing a reasonable and efficient transportation system of temporary elevators according to construction project characteristics and project team requirements, is one of the important tasks in construction [11][12]. The content of temporary elevator planning mainly includes two aspects: configuration and operation planning. Configuration planning refers to determining the number, type, and location of temporary elevators, and it belongs to the macro-level of planning [11]. Operation planning refers to determining the transportation sequence and motion route of temporary elevators, and it belongs to the micro-level of planning [12]. However, from the perspective of spatio-temporal planning, the following two points are often ignored in conventional temporary elevator planning: 1) transportation demands of temporary elevators fluctuate significantly and frequently at different stages of a construction project, and ideally, the service date of each temporary elevator and the loading and unloading service floors of its cabs on each service date are determined accordingly to meet specific transportation demands [11][13][14][15]; and 2) the availability of time and space is limited in a construction project, and it is essential that the workload level of a temporary elevator cab and the demand level of its loading and unloading service floors on a service date related to time availability, as well as the work status of a temporary elevator cab and the use status of its loading and unloading service floors in a transportation task related to space availability, are considered [12][16].

The typical process of temporary elevator planning is to select tentative planning solutions from a large number of candidates and determine the final planning solution by comparing the selected tentative planning solutions. Currently, the display of planning solutions in the process mainly adopts abstract (e.g., text), low-dimensional (e.g., 2D drawing), and static (e.g., 3D model) ways. However, for temporary elevator planning, such practices cannot clearly show planning elements and efficiently convey planning information, making planning solutions hard to be fully understood by the project team. What is more, the spatio-temporal planning of temporary elevators puts forward higher requirements for the display of planning solutions due to the complexity considering both time and space, which can become challenging to the project team [13]. Even when the 4D model is adopted, the display effect of spatio-temporal planning solutions is still limited. Therefore, a customized display way, especially for the spatio-temporal planning of temporary elevators, is eagerly expected. The game engine is a platform capable of developing visual products with a virtual and interactive experience, and it has the potential to display the complex content of spatio-temporal planning solutions of temporary elevators intuitively and conveniently [17][18].

With that background, this research presents a spatio-temporal planning simulation of temporary elevators in construction using a game engine to address the above limitations. The rest of this paper is organized as follows. Section 2 elaborates the workflow of spatio-temporal planning simulation. An experimental test is provided in Section 3. Section 4 gives the conclusion and outlook.

2 Spatio-Temporal Planning Simulation Workflow

The workflow of the spatio-temporal planning simulation of temporary elevators in construction using a game engine is shown in Figure 1. It consists of three steps: the first step is to import data into the game engine platform, the second step is to generate the spatio-temporal planning simulation scheme, and the third step is to conduct the spatio-temporal planning simulation. They are elaborated in the following subsections.

2.1 Step 1: Import Data into the Game Engine Platform

In Step 1, the data required for the spatio-temporal planning simulation is imported into the game engine platform.

The imported data comes from the project BIM model, the project schedule, and the spatio-temporal configuration and operation planning solutions. The first two categories will be used to generate the 4D model of the project, and the last category will be used to generate the spatio-temporal configuration and operation planning simulation schemes.

Figure 2 shows the data model diagram of the spatio-temporal configuration and operation planning solutions divided into five parts. The “Temporary Elevator” component comprises the specification (i.e., rated velocity, acceleration, and deceleration) of each temporary elevator. The “Service Date” component comprises the service date of each temporary elevator, and each temporary elevator has only one set of service date data. The “Service Floor” component comprises the loading and unloading service floors of each temporary elevator cab on each service date, and each temporary elevator has one or multiple set(s) of service floor data. The “Transportation Task” component comprises the transportation sequence of each transportation task and its assigned temporary elevator cab on each service date, and each temporary elevator has one or multiple set(s) of transportation task data. The “Motion Route” component comprises the stop sequence and resource quantity of loading and unloading service floors in each transportation task, and each transportation task has one or multiple set(s) of motion route data.

2.2 Step 2: Generate the Spatio-Temporal Planning Simulation Scheme

In Step 2, the spatio-temporal planning simulation scheme is generated according to the imported data, and it is divided into the configuration and operation planning simulation schemes.

In the configuration simulation scheme, the configured temporary elevators and the loading and unloading service floors of their cabs on each service date are necessarily involved, and they are directly determined by the imported spatio-temporal configuration planning solution. Meanwhile, the workload level of the temporary

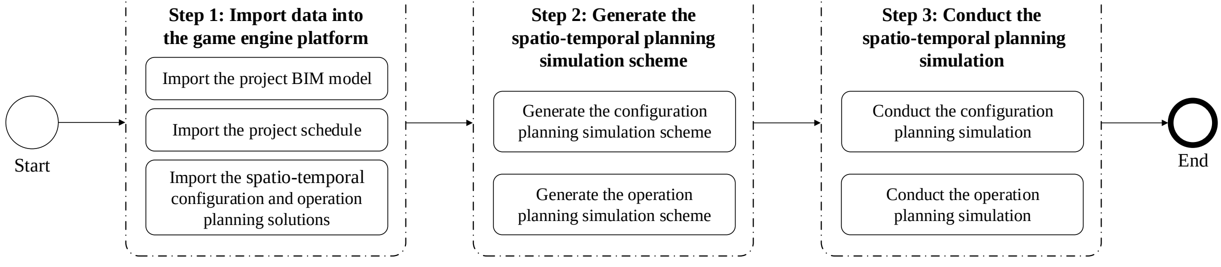

Figure 1. Workflow of the spatio-temporal planning simulation using a game engine

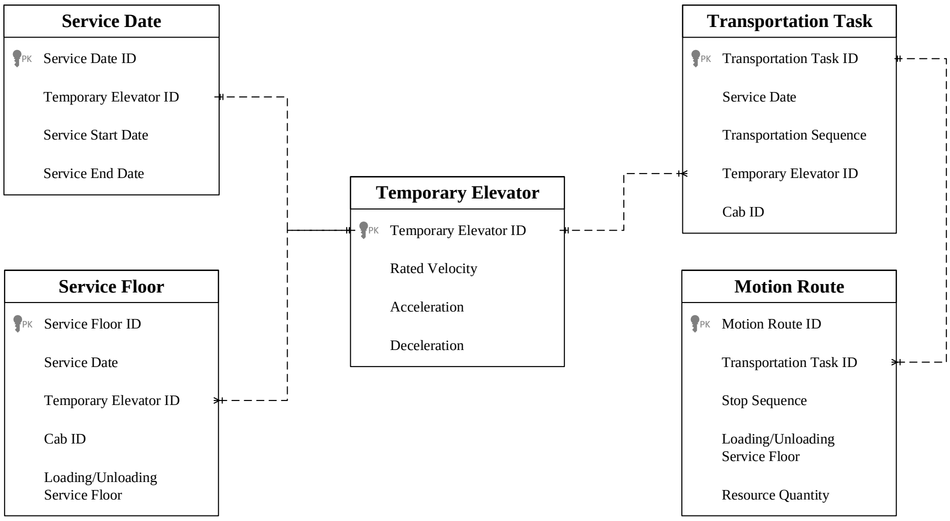

Figure 2. Data model diagram of the spatio-temporal configuration and operation planning solutions

elevator cabs and the demand level of the loading and unloading service floors, related to time availability, are especially focused. The workload of a temporary elevator cab on a service date is measured by the total time of all the transportation tasks it performs. The demand of a loading or unloading service floor on a service date is measured by the quantity of the resources loaded or unloaded on the floor. The workload of temporary elevator cabs and the demand of loading and unloading service floors are divided into three levels: low, medium, and high, and the range of each level is defined based on the actual consideration of the project team.

In the operation planning simulation scheme, the assigned temporary elevator cab and its loading and unloading service floors in each transportation task are necessarily involved, and they are directly determined by the imported spatio-temporal operation planning solution. Meanwhile, the work status of the temporary elevator cab and the use status of the loading and unloading service floors, related to space availability, are especially focused. The work of temporary elevator cabs is divided into five statuses: waiting, no-load moving, loading, loaded moving, and unloading. The use of loading and unloading service floors is divided into four statuses: vacating, vacant, occupying, and occupied. They are both determined according to time details of a transportation task.

In the figuration and operation planning simulation schemes, the time of a transportation task is determined by the motion time of the temporary elevator cab, the operation time of the temporary elevator cab door, and the transfer time of transported resources, as expressed in Equation (1). If the motion distance from the current stop floor to the next stop floor is greater than or equal to the distance required for the temporary elevator cab to accelerate from zero to the rated velocity and then decelerate to zero, the motion time is determined by the first fraction of Equation (2), otherwise by the second fraction of Equation (2). Equation (2) is derived from the acceleration and deceleration equations, and the condition is that the final velocity at the end of acceleration equals the initial velocity at the beginning of deceleration.

$$T_{d,t}^{T} = \sum_{s=1}^{N_{d,t}^{S}} \left(T_{d,t,s}^{M} + T_{d,t,s}^{O} + T_{d,t,s}^{C} + T_{d,t,s}^{B} + T_{d,t,s}^{E}\right) \quad (1)$$

$$T_{d,t,s}^{M} = \begin{cases} \frac{V_e^R}{V_e^A} + \frac{V_e^R}{V_e^D} + \frac{D_{d,t,s}^{M} - \frac{{V_e^R}^2}{2V_e^A} - \frac{{V_e^R}^2}{2V_e^D}}{V_e^R}, D_{d,t,s}^{M} \geq \frac{{V_e^R}^2 (V_e^A + V_e^D)}{2V_e^A V_e^D} \\ \sqrt{\frac{2D_{d,t,s}^{M}}{\begin{vmatrix} {V_e^A}^2 & -{V_e^D}^2 \\ V_e^A & V_e^D \end{vmatrix}}} \left(V_e^A + V_e^D\right), D_{d,t,s}^{M} < \frac{{V_e^R}^2 (V_e^A + V_e^D)}{2V_e^A V_e^D} \end{cases} \quad (2)$$

where $T_{d,t}^{T}$ is the time of transportation task t on service date d; $N_{d,t}^{S}$ is the number of segment s in transportation task t on service date d; $T_{d,t,s}^{M}$ is the temporary elevator cab motion time in segment s of transportation task t on service date d; $T_{d,t,s}^{O}$ and $T_{d,t,s}^{C}$ are the times of opening and closing door in segment s of transportation task t on service date d, respectively; $T_{d,t,s}^{B}$ and $T_{d,t,s}^{E}$ are the times of boarding and exiting the temporary elevator cab in segment s of transportation task t on service date d, respectively; $D_{d,t,s}^{M}$ is the temporary elevator cab motion distance in segment s of transportation task t on service date d; and V_e^R, V_e^A, and V_e^D are the rated velocity, acceleration, and deceleration of temporary elevator e, respectively.

2.3 Step 3: Conduct the Spatio-Temporal Planning Simulation

Based on the generated configuration and operation planning simulation schemes, the spatio-temporal

Table 1. Color code in the temporary elevator configuration planning simulation

Planning element	Workload level	Demand level	Color
Temporary elevator cab	Low	-	Light red
	Medium		Medium red
	High		Dark red
Loading service floor	-	Low	Light yellow
		Medium	Medium yellow
		High	Dark yellow
Unloading service floor	-	Low	Light blue
		Medium	Medium blue
		High	Dark blue

planning simulation is conducted in Step 3.

Although planning elements, including temporary elevators and loading and unloading service floors, can be dynamically visualized in the 4D model, it does not highlight the planning elements and cannot distinguish changes in their levels and statuses, making the planning elements difficult to identify and the changes in their levels and statuses unable to monitor. The hue (e.g., red, yellow, blue) and value (e.g., light red, medium yellow, dark blue) of colors refer to their appearance and lightness, respectively, which both belong to the basic characteristics of color [19][20]. The colors with specific hues and values can effectively distinguish different marked objects and their changes, respectively [21][22]. In order to display spatio-temporal planning solutions intuitively and conveniently, the display way of combining the hue and value of colors and the 4D model is adopted in the spatio-temporal planning simulation.

In the configuration planning simulation, the color code for the workload level of temporary elevator cabs and the demand level of their loading and unloading service floors on a service date are listed in Table 1. Temporary elevator cabs and loading and unloading service floors are marked using red, yellow, and blue, respectively. For temporary elevator cabs, the low, medium, and high workload levels are light, medium, and dark, respectively. For loading and unloading service floors, the low, medium, and high demand levels are light, medium, and dark, respectively. In this way, different levels of planning elements on a service date can be highlighted accordingly.

In the operation planning simulation, the work status of a temporary elevator cab and the use status of its loading and unloading service floors in a transportation task are listed in Table 2. Temporary elevator cabs, current and other loading service floors, and current and other unloading service floors are marked using red, yellow, green, blue, and purple, respectively. For temporary elevator cabs, the waiting, no-load moving, loading, loaded moving, and unloading work statuses are light, dark, medium, dark, and medium, respectively. For current loading service floors, the occupied and vacating use statuses are medium and dark, respectively. For other loading service floors, the vacant and occupied use statuses are light and medium, respectively. For current unloading service floors, the vacant and occupying use

Table 2. Color code in the temporary elevator operation planning simulation

Planning element	Category	Work status	Use status	Color
Temporary elevator cab	-	Waiting	-	Light red
		No-load moving		Dark red
		Loading		Medium red
		Loaded moving		Dark red
		Unloading		Medium red
Loading service floor	Current	-	Occupied	Medium yellow
			Vacating	Dark yellow
	Other	-	Vacant	Light green
			Occupied	Medium green
Unloading service floor	Current	-	Vacant	Light blue
			Occupying	Dark blue
	Other	-	Vacant	Light purple
			Occupied	Medium purple

statuses are light and dark, respectively. For other unloading service floors, the vacant and occupied use statuses are light and medium, respectively. In this way, different statuses of planning elements in a transportation task can be highlighted accordingly.

3 An Experimental Test

Based on the presented spatio-temporal planning simulation workflow, an experimental test was performed using Unity. The BIM model was exported from Revit, and the schedule and the spatio-temporal configuration and operation planning solutions were exported from MySQL. The planning simulation schemes were generated and the planning simulation was conducted by the scripts in C#.

The case that two temporary elevators serve three dates was taken as the test of configuration planning simulation. Table 3 lists the configuration planning simulation scheme. By simulation, the configuration planning is shown in Figure 3. On service date 1, cab 1 of temporary elevator 1 is marked in dark red, its loading service floors 1, 5, and 9 are marked in dark, medium, and medium yellow respectively, and its unloading service floors 1, 5, and 9 are marked in dark, medium, and dark blue respectively; and cab 2 of temporary elevator 1 is marked in medium red, its loading service floors 1 and 8 are marked in medium and light yellow respectively, and its unloading service floors 1 and 8 are marked in light and medium blue respectively. On service date 2, cab 1 of temporary elevator 1 is marked in light red, its loading service floors 1 and 11 are both marked in light yellow, and its unloading service floors 1 and 11 are both marked in light blue; cab 2 of temporary elevator 1 is marked in dark red, its loading service floors 1 and 7 are marked in dark and medium yellow respectively, and its unloading service floors 1 and 7 are marked in medium and dark blue respectively; cab 1 of temporary elevator 2 is marked in medium red, its loading service floors 1 and 6 are marked in light and medium yellow respectively, and its unloading service floors 1 and 6 are marked in medium and light blue respectively; and cab 2 of temporary elevator 2 is marked in dark red, its loading service floors 1, 10, and 12 are marked in medium, dark, and dark yellow respectively, and its unloading service floors 1, 10, and 12 are marked in dark, light, and dark blue respectively. On service date 3, cab 1 of temporary elevator 2 is marked in light red, its loading service floors 1 and 13 are both marked in light yellow, and its unloading service floors 1 and 13 are both marked in light blue; and cab 2 of temporary elevator 2 is marked in dark red, its loading service floors 1 and 15 are marked in medium and dark yellow respectively, and its unloading service floors 1 and 15 are marked in dark and medium blue respectively.

The case that one temporary elevator cab serves two loading floors and two unloading floors in a transportation task was taken as the test of operation planning simulation. Table 4 lists the operation planning simulation scheme. By simulation, the operation planning is shown in Figure 4. In Step 1, cab 2 of temporary elevator 1, loading service floors 5 and 8, and unloading service floors 11 and 12 are marked in dark red,

Table 3. Temporary elevator configuration planning simulation scheme

Temporary elevator	Service date	Cab	Workload level	Service floor	Demand level	
					Loading	Unloading
1	1	1	High	1	High	High
				5	Medium	Medium
				9	Medium	High
		2	Medium	1	Medium	Low
				8	Low	Medium
	2	1	Low	1	Low	Low
				11	Low	Low
		2	High	1	High	Medium
				7	Medium	High
2	2	1	Medium	1	Low	Medium
				6	Medium	Low
		2	High	1	Medium	High
				10	High	Low
				12	High	High
	3	1	Low	1	Low	Low
				13	Low	Low
		2	High	1	Medium	High
				15	High	Medium

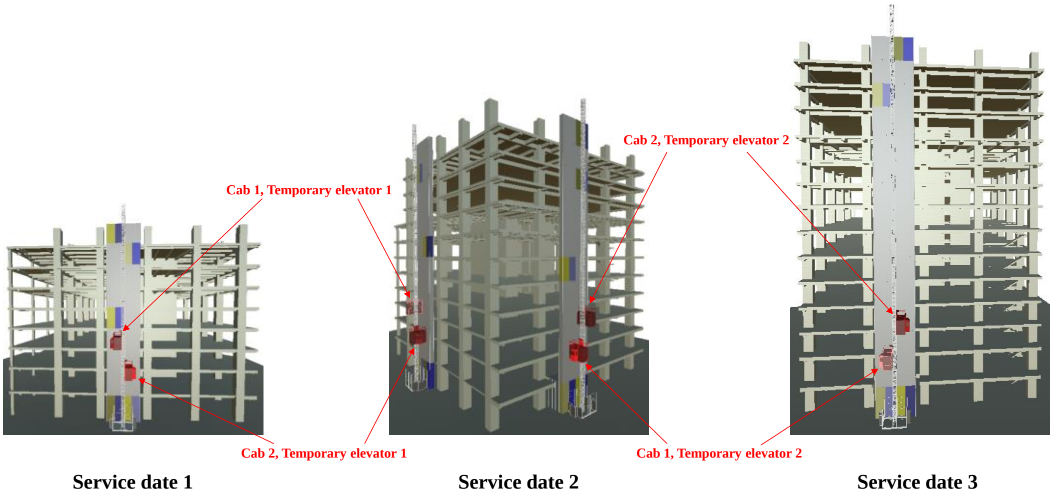

Figure 3. Temporary elevator configuration planning simulation

Figure 4. Temporary elevator operation planning simulation

medium yellow, medium green, light purple, and light purple, respectively. In Step 2, they are marked in medium red, dark yellow, medium green, light purple, and light purple, respectively. In Step 3, they are marked in dark red, light green, medium yellow, light purple, and light purple, respectively. In Step 4, they are marked in medium red, light green, dark yellow, light purple, and light purple, respectively. In Step 5, they are marked in dark red, light green, light green, light blue, and light purple, respectively. In Step 6, they are marked in medium red, light green, light green, dark blue, and light purple, respectively. In Step 7, they are marked in dark red, light green, light green, medium purple, and light blue, respectively. In Step 8, they are marked in medium red, light green, light green, medium purple, and dark blue, respectively. In Step 9, they are marked in light red, light green, light green, medium purple, and medium purple, respectively.

Through such displays, not only are the configured temporary elevators and the loading and unloading service floors of their cabs on a service date and the assigned temporary elevator cab and its loading and unloading service floors in a transportation task highlighted, but the changes in the workload levels of the temporary elevator cabs (i.e., low, medium, and high) and the demand levels of the loading and unloading service floors (i.e., low, medium, and high) as well as the work statuses of the temporary elevator cab (i.e., waiting, no-load moving, loading, loaded moving, and unloading), and the use statuses of the loading and unloading service floors (i.e., vacating, vacant, occupying, and occupied) can also be distinguished. Thus, the planning elements are easy to identify, and the changes in their levels and statuses are able to monitor, facilitating the detection of potential problems and the comparison among different planning solutions.

4 Conclusion and Outlook

To clearly show planning elements and efficiently convey planning information, this research presents the spatio-temporal planning simulation of temporary elevators in construction using a game engine. The presented workflow consists of importing data into the game engine platform, generating the spatio-temporal planning simulation scheme, and conducting the spatio-temporal planning simulation. In configuration and operation planning simulation, in addition to the planning elements necessarily involved, their levels and status are especially focused. From the results of the experimental test, the presented spatio-temporal planning simulation was intuitive and convenient, various planning elements were clearly shown, and corresponding planning information was efficiently conveyed, which could effectively enhance the display effect of spatio-temporal planning solutions. Training in advance in the virtual

Table 4. Temporary elevator operation planning simulation scheme

Stage	Planning element	Work status	Use status
1	Cab 2, Temporary Elevator 1	No-load moving	-
	Current loading floor 5	-	Occupied
	Other loading floor 8	-	Occupied
	Other unloading floor 11	-	Vacant
	Other unloading floor 12	-	Vacant
2	Cab 2, Temporary Elevator 1	Loading	-
	Current loading floor 5	-	Vacating
	Other loading floor 8	-	Occupied
	Other unloading floor 11	-	Vacant
	Other unloading floor 12	-	Vacant
3	Cab 2, Temporary Elevator 1	Loaded moving	-
	Other loading floor 5	-	Vacant
	Current loading floor 8	-	Occupied
	Other unloading floor 11	-	Vacant
	Other unloading floor 12	-	Vacant
4	Cab 2, Temporary Elevator 1	Loading	-
	Other loading floor 5	-	Vacant
	Current loading floor 8	-	Vacating
	Other unloading floor 11	-	Vacant
	Other unloading floor 12	-	Vacant
5	Cab 2, Temporary Elevator 1	Loaded moving	-
	Other loading floor 5	-	Vacant
	Other loading floor 8	-	Vacant
	Current unloading floor 11	-	Vacant
	Other unloading floor 12	-	Vacant
6	Cab 2, Temporary Elevator 1	Unloading	-
	Other loading floor 5	-	Vacant
	Other loading floor 8	-	Vacant
	Current unloading floor 11	-	Occupying
	Other unloading floor 12	-	Vacant
7	Cab 2, Temporary Elevator 1	Loaded moving	-
	Other loading floor 5	-	Vacant
	Other loading floor 8	-	Vacant
	Other unloading floor 11	-	Occupied
	Current unloading floor 12	-	Vacant
8	Cab 2, Temporary Elevator 1	Unloading	-
	Other loading floor 5	-	Vacant
	Other loading floor 8	-	Vacant
	Other unloading floor 11	-	Occupied
	Current unloading floor 12	-	Occupying
9	Cab 2, Temporary Elevator 1	Waiting	-
	Other loading floor 5	-	Vacant
	Other loading floor 8	-	Vacant
	Other unloading floor 11	-	Occupied
	Other unloading floor 12	-	Occupied

environment of real situations is beneficial to actual work. Future research will focus on developing a virtual reality training program for the spatio-temporal planning of temporary elevators in construction by exploiting game engine technologies.

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