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SPACE ZONING CONCEPT-BASED SCHEDULING MODEL FOR REPETITIVE CONSTRUCTION PROCESS

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Abstract. Many researchers have studied effective space zoning to reduce the duration of a construction project and interference among work tasks. These studies, however, attempted to plan the construction schedule using the space zoning concept based on network-based scheduling methods. Accordingly, it was difficult to reflect the representative characteristics of space zoning, such as iteration and overlapping. To overcome such limitations of existing methodologies and to achieve schedule reduction of a construction project by maximizing productivity, a Space zoning Concept-based scHEduling ModEl (SCHEME) for repetitive construction processes that adopt simulation techniques was developed in this study. The result of the application of the developed model to actual construction cases shows that the model reflects well the space-zoning characteristics, and in terms of the reduction of the construction duration, the model yielded a superior outcome in nonspace-zoning cases. The model developed in this study is expected to produce an excellent effect on the repetitive construction processes, in terms of construction duration.

Keywords: space zoning; scheduling; computer aided simulation; process model.

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Introduction

Along with the reduction of construction cost, the effort to reduce construction duration has been a long-studied subject in the construction industry. Methods like fast track, concurrent engineering, and phased construction are continuously being studied to reduce the duration of a construction project. Aside from studying macro-level management techniques that mainly dealt with the high-level works in the construction work breakdown structure (i.e. foundations, structure, finishing works, etc.), research has been consistently conducted to reduce the duration of a construction project and to improve productivity by "planning" or "zoning" of a working space in terms of micro-level. Workspace zoning results in effective construction as it can reduce not only the construction duration through the iteration and overlapping of the related activities but also the congestion and interference among the work tasks or resources in a project (Akinci *et al*. 2002; Cheung, O'Connor 1996; Guo 2002; Li, Love 1998; Thabet, Beliveau 1994; Tommelein, Zouein 1993; Winch, North 2006; Yeh 1995; Zouein, Tommelein 2001). In spite of such advantages, the existing studies focus on the development of a methodology for the efficient implementing of space zoning, such as securing and efficiently distributing a work space. Moreover, while a few research have tried to develop a scheduling model that integrates space zoning concept into the existing scheduling method (e.g. Critical Path Method, CPM and line of balance, LOB), it turns out that there are several limitations for them in terms of representing a characteristic of space zoning (Akinci *et al*. 2002; Cho, Eppinger 2005; Guo 2002; Smith, Morrow 1999; Thabet, Beliveau 1994; Winch, North 2006; Zouein, Tommelein 2001). Therefore, this study aims at developing a Space zoning Concept-based scHEduling ModEl (SCHEME) for repetitive construction processes that can overcome the limitations of the existing network-based scheduling methods (i.e. CPM and PERT) and LOB method for space zoning.

To build such a model, this study was conducted in three phases. First, literature review including the concept of space zoning was analyzed. Second, based on the results from literature review, SCHEME for

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effective space zoning was developed. For developing the model, this research adopts discrete-event simulation methods, so that the model can represent the characteristic of space zoning appropriately. Finally, the model that was developed in the second phase was applied to steel structure construction, a representative repetitive work in high-rise buildings that actively use space zoning, in order to verify and examine the developed model.

1. State of the art

In general, space zoning is applied to repetitive construction operations to reduce duration and minimize interference among the different works involved (Akinci *et al.* 2002; Guo 2002; Thabet, Beliveau 1994; Winch, North 2006; Zouein, Tommelein 2001). When as many as *i* activities in precedence relations are performed on one floor (i.e. floor 1) with a traditional construction method (i.e. nonspace zoning), as shown in Fig. 1(a), the construction time can be expressed by the sum of the duration of each activity on floor 1. Using space zoning, however, the total duration becomes shorter than the duration of the case without space zoning, as shown in Figures 1(b) and 1(c). That is, if one floor (i.e. floor 1) is divided into *j* zones and each activity is performed by iteration and overlapping, the total duration is reduced compared to the duration in which each activity proceeds in an orderly manner. Figures 1(b) and 1(c) Show the concepts of ideal and actual space zoning concept based on the combination of the durations of the activities. If the duration of each activity is not identical on each zone, as shown in Fig. 1(c), the float time occurs, in which the work of a following zone does not start right after the work in the previous zone ends.

The concept of such space zoning can be explained by the status of the activities that occurs in the time flow. As shown in Fig. 2, when a floor is divided into four zones and when four activities exist on the floor, the work follows from "state 1" in Fig. 2(a) to "state 4" in Fig. 2(d). In other words, state 1 is the state in which activity 1 in zone 1 has been completed, and to go to state 2, activity 1 moves to the work in zone 2, as indicated by the arrow. State 2 is the state in which activity 1 is completed in zone 2, and activity 2 is completed in zone 1. Activities 1 and 2 move to zones 3 and 2, respectively. Therefore, using the space zoning concept, activities are repeated in each zone. Moreover, the activities in the divided zones are performed simultaneously, causing overlap among them.

There are a number of previous studies on space zoning. Winch and North (2006) developed a decision-making support tool via the identification and arrangement of work spaces for efficient construction.

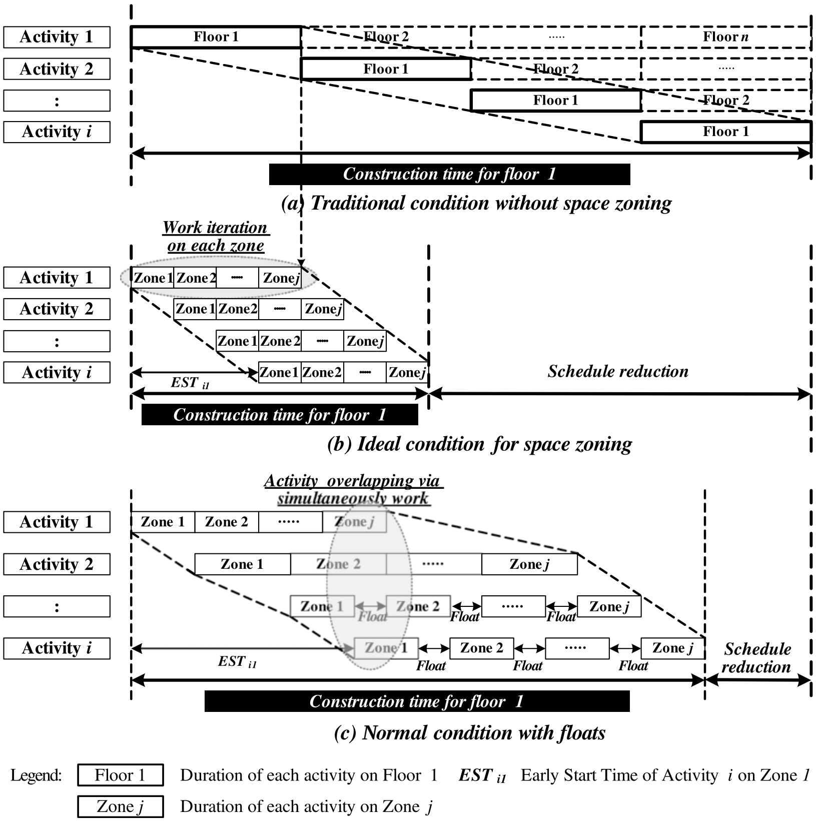

Fig. 1. Concept of space zoning

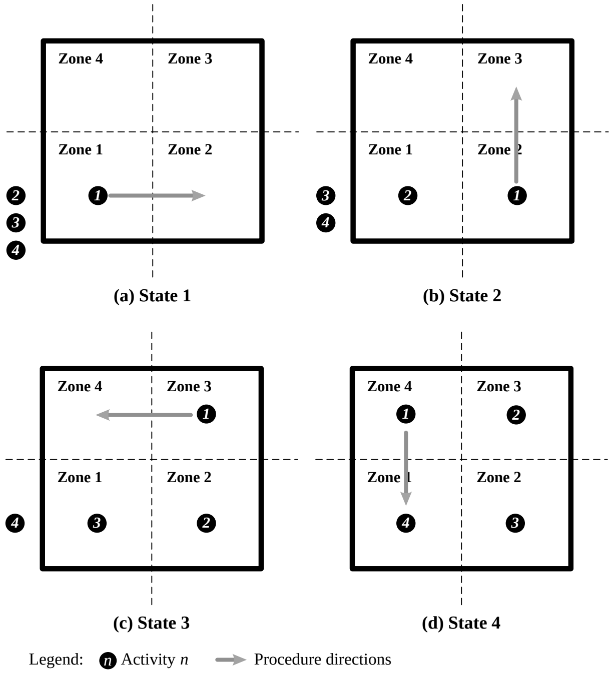

Fig. 2. Cycles of work activities by space zoning

Guo (2002) presented a solution to productivity loss due to the constraints and path interference in a work space. Akinci *et al.* (2002) discussed the types of time–space conflicts due to such space constraints and, based on such discussion, proposed a method that determines the precedence of activities. Finally, Zouein and Tommelein (2001) analyzed the trade-off between time and space through the adjustment of the activity duration and the proposed space-scheduling algorithms, by adjusting the starting time of each activity. These studies focus on the development of a methodology for the efficient performance of space zoning, such as securing and efficiently distributing a work space. There are few studies, however, on reducing the construction duration and improving productivity through space zoning. Furthermore, despite the fact that space zoning often focuses on repetitive works in the actual construction field, previous studies did not adequately address the problems of iteration and overlapping of activities.

Meanwhile, network-based project-scheduling methods (i.e. PERT or CPM) can model such iteration and overlapping characteristics only to a limited extent (Cho, Eppinger 2005; Smith, Morrow 1999; Thabet, Beliveau 1994). In other words, the iteration of the works that occur in the divided zone and on each floor cannot be effectively expressed by the existing CPM or PERT method. Moreover, the existing CPM or PERT method cannot effectively solve the overlapping of activity in the divided zone and on each floor, which are caused by concurrent operations of activities. Moreover, as pointed out by Smith and Morrow (1999), network-based scheduling methods lack the function of predicting and managing the duration and productivity change based on key scheduling points (e.g. resource constraints, logical-precedence relationship, and stochastic task duration).

The LOB method has been developed for more efficient schedule management of projects with repetitive iteration and overlapping processes (Arditi, Albulak 1986; Arditi *et al.* 2001, 2002; Halpin, Riggs 1992). Despite numerous studies for LOB, it is hard to apply the LOB concept to space zoning scheduling due to following aspects: (1) space constraints and (2) interaction among unit works:

(1) According to the existing research about LOB, basically LOB pursues the optimization (or balancing) among the unit works through consideration of production rate for those works, so that the unit works can be conducted smoothly in terms of the minimization of the idle time on each work. Thus, there is a limitation for recognizing space dependencies in LOB, as appointed by Arditi *et al.* (2002). However, space zoning method has been developed in optimization depending on space constraints. Namely, in space zoning, the scheduling should be established according to how the most effective production rate could be achieved for the given space constraints.

(2) In LOB, firstly all production rates for each work should be calculated, respectively, and then each of them could be accumulated as an entire schedule. As such, it is hard to identify the influence between each work, when the changes on the amount of the input resource for each work may occur. Consequently, there is a limitation for updating project schedule by increasing the production rate of selected activities (Arditi *et al.* 2002). However, the space zoning concept in this paper could identify the effect of resource variation on the production rate of particular unit work, and furthermore it is available to easily update the influence of such a unit work to other unit works in terms of project schedule.

Additionally, the LOB technique is one of the deterministic methodologies, and therefore, is (1) limited in assuming the uniform production rate of each activity (Arditi *et al.* 2001), and (2) lacking in the consideration of uncertainty, which is unavoidable in construction works.

As shown above, it turns out that the existing scheduling methods have a limitation for representing the characteristics of space zoning, such as (1) iteration and overlapping and (2) resource and space constraints. Thus, there is a need for developing a scheduling model which has an approach for overcoming above constraints.

2. Development of SCHEME

Discrete event simulation is effective in calculating the productivity and duration of repetitive construction processes, and in fact, various successful applications of discrete-event simulation can be witnessed in the construction field (Halpin, Riggs 1992; Hong *et al.* 2011; Lee *et al.* 2009). In other words, simulation methodologies have been applied to construction projects to measure the productivity of repetitive processes based on the resource constraints. Such methodologies have considered iteration and overlapping, which are difficult issues that the existing network-based CPM or PERT methods can address (Adler *et al.* 1995; Browning, Eppinger 2002; Taylor III, Moore 1980). Unlike the LOB technique, the simulation methodology makes it easy to determine changes in project schedule depending on the changes of the resources and duration at the activity level, and to resolve the uncertainty of a project. Therefore, based on the space zoning concept as explained in Figures 1 and 2, SCHEME was developed in this study adopting simulation techniques, especially modeling elements of CYCLONE which is one of the well-recognized discrete-event simulation methods. For more information regarding CYCLONE, including its modeling elements, please refer to Halpin and Riggs (1992).

2.1. Model framework

2.1.1. Precedence constraints

The logical relationship among activities (i.e. precedence relationship) can be modeled using the COMBI and QUE elements of CYCLONE. The COMBI element of CYCLONE can start only after the precedent conditions are met (Halpin, Riggs 1992). That is, as shown in "A" (nodes 2, 5, 9, and 10) in Fig. 3, the work of activity 1 is a COMBI element (node 2). Therefore, in order to implement it, the precedent conditions (i.e. nodes 1, 3, and 4) should have been prepared. In addition, since activity 2 (node 10), which is a succeeding work of activity 1, is also a COMBI element, the three precedent conditions (nodes 9, 11, and 12) should have been prepared, in order to initiate activity 2. Therefore, once the model begins, activity 2 (node 10) can begin only after the "zone available" defined in node 1 completes activity 1 (nodes 2 and 5) and is in a "ready" state after arriving at node 9. In this study, the precedence relationship among activities is modeled based on the defined zone. Meanwhile, "Done (nodes 5 and 13)" is a dummy node set for the precedence relationship of a CYCLONE model and does not affect the measurement of the actual duration and productivity.

2.1.2. Iteration

Iteration in space zoning occurs in two types: (1) the type in which an activity is repeated while moving to the divided zones, and (2) the type in which an activity is repeated by the floor. "B" (nodes 9–16) in Fig. 3 is a model of the process in which activity 2 is repeated by the number of zones defined in the model. In other words, by connecting node 13 to the work loop (i.e. the path from node 13 to node 15, and returning to node 9), the model allows a repetitive work as many times as the number of zones (i.e. the number indicated in node 1), each of which is to be "ready" in node 9 after the completion of activity 1. An

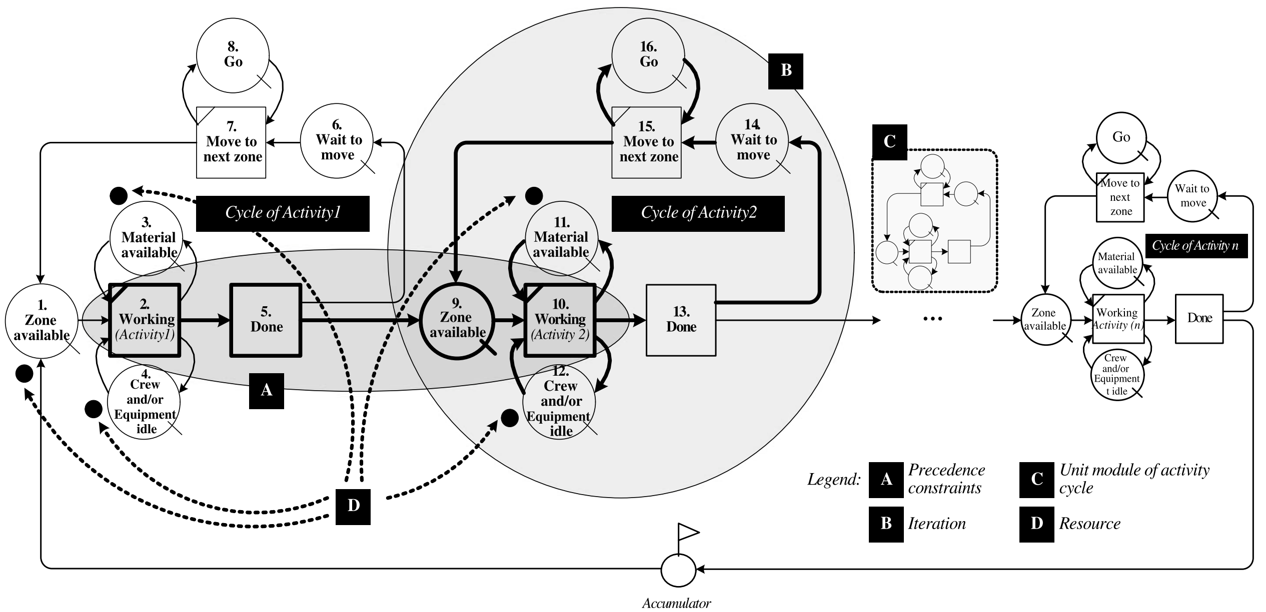

Fig. 3. Space zoning concept-based scheduling model

accumulator is also used as the final node of the model, as shown in Fig. 3, which is connected to node 1 so that activities are repeated by the floor. In other words, this accumulator means that activity *n*, the final activity, is completed in work zone 1, and as it is connected to node 1 by the accumulator, activity 1 repeats their work on zone 1 of the next floor.

2.1.3. Expansion of the model framework

As shown in Fig. 3, the developed SCHEME has the following structures: (1) according to the flow of the "zone" resource presented in node 1 as explained in "Precedence Constraints," the precedent and subsequent works were performed, and (2) as explained in "Iteration," the model repeats each work cycle (i.e. "B" in Fig. 3), depending on the number of zones. Furthermore, based on the user-defined number of work activities, the unit module of the activity cycle, expressed as "B" and "C" in Fig. 3, can be "added on" flexibly according to the order of the activities. In other words, if there is a total of four activities, the activity cycle will have four unit modules, such as "B" or "C" in Fig. 3. In addition, if there are additional work tasks aside from the work (node 2) and movement (node 7) according to the content of the activity, the activity cycle can be adjusted based on the work loop part (i.e. nodes 6–8 or nodes 14–16) so as not to damage the "precedence relationship".

2.2. Model constructs

2.2.1. Resource constraints

As explained with the space zoning concept and precedence constraints, only after the preparation of the "space" with the completion of the precedent works, the subsequent work could be initiated. Therefore, the developed model considered "space" as a core resource for running the model. As the number of input activities and the duration of each activity in each zone are adjusted according to the number of zones in this "space," the work space in the developed model is a very important resource. As shown in "D" in Fig. 3, the resources in the developed model are defined as the crew or equipment (nodes 4 and 12) and as the material (nodes 3 and 11) for each activity, as well as the space (node 1). The "•" of "D" in Fig. 3 indicates the number of each resource. For example, if there are four "•" in node 1, it means that one floor has been divided into four working zones.

2.2.2. Activity duration

The duration of the activities in the CYCLONE model is described in the COMBI and NORMAL elements (Halpin, Riggs 1992). As shown in Fig. 3, nodes 2 and 7 are "activity working time" and "the transition time to the next zone" on cycle of activity 1, and node 5 is a dummy variable for the aforementioned "precedence constraints." According to Halpin and Riggs (1992), such activity duration can be calculated using various methods as well as past experience, estimates, the deterministic value by experts, and the use of prediction models. A more detailed measurement process of duration will be explained in "MODEL APPLICAION."

2.3. Model implementation

2.3.1. Calculating cycle time

As shown in Figures 1 and 2, the space zoning results in the cyclic repetition of activities in the divided zones. Thus, the cycle time per floor can be calculated by adding the early starting time (i.e. EST_{i1}) of the final activity and the time that it takes the activity to work from zone 1 to zone *j*, as in Fig. 1(b) and 1(c). Moreover, in the normal condition (i.e. Fig. 1c), a float time may exist between zones. Therefore, one cycle time per floor with both *i* of activities and *j* of zones (CT_{ij}) can be estimated using the following equation:

$$CT_{ij} = EST_{i1} + \sum_{n=1}^{j} D_{in} + \sum_{n=1}^{j} F_{in}, \quad \text{for } n = 1 \text{ to } j, \tag{1}$$

where EST_{i1} = the early starting time of activity *i* in zone 1, D_{in} = the duration of activity *i* in zone *n* (for $n = 1$ to *j*), and F_{in} = the float time of activity *i* between the completion time of zone *n* and the starting time of zone $n+1$ (for $n = 1$ to *j*). Meanwhile, as shown in Fig. 1, EST_{i1} is the time that it takes activity *i* to start the work in zone 1, which can be expressed as the sum of the working durations from activity 1 to activity $i-1$ in zone 1. Therefore, EST_{i1} in Eqn (1) can be calculated using the following equation:

$$EST_{i1} = T_0 + \sum_{n=1}^{i-1} D_{n1}, \quad \text{for } n = 1 \text{ to } i-1, \tag{2}$$

where T_0 = the *EST* of activity 1 in zone 1, and D_{n1} = the duration of activity *n* in zone 1 (for $n = 1$ to $i-1$). As shown in Fig. 1, the float time in Eqn (1) is the delay time of activity *i* during the working process of each zone. Therefore, the float time is the difference between the completion time of zone $j-1$ and the starting time of zone *j* in each activity. Therefore, it can be calculated using the following equation:

$$\sum_{n=1}^{j} F_{in} = \sum_{n=1}^{j-1} (ST_{i\,n+1} - FT_{in}), \quad \text{for } n = 1 \text{ to } j-1, \tag{3}$$

where $ST_{i\,n+1}$ = the starting time of activity *i* in zone $n+1$, and FT_{in} = the finishing time of activity *i* in zone n. The duration of each activity on the developed model (i.e. Fig. 3) is defined in the COMBI and NORMAL elements of each activity cycle. Moreover, the "float time" is calculated by the combination of the QUE and COMBI elements. For example, as explained in *Precedence Constraints*, only when precedent activity 1 completes and zone 1 is "ready" in node 9, the subsequent activity 2 should be begun. Therefore, if the duration of activity 1 becomes delayed, then activity 2 will be in a queue state, and float time will occur. The model in this study was developed in such a way that the waiting time becomes the float time as expressed in Eqn (3).

2.3.2. Finding the optimal cycle time

As shown in Fig. 1(b), an ideal space zoning means that, due to the duration (D_{ij}) of each activity identical to the others, the flow of work on each zone becomes smooth, without a float time (i.e. $\sum_{n=1}^{j} F_{in} \approx 0$). Meanwhile, D_{ij} generally changes based on the amount of input resources (Chang *et al.* 2007; Cho *et al.* 2011; El-Rayes, Moselhi 1998; Hyari, El-Rayes 2006). Therefore, in order to achieve an ideal zoning space, the input resource into each activity should be adequately planned. The developed model calculated the optimal cycle time based on the change in the resources. That is, by examining the change in the cycle time while changing the amount of the resources included in the model, the optimal cycle time of the established model can be calculated. If there are i activities in j zones and the equipment and crew input in each activity are defined as E_1 to E_i and C_1 to C_i, respectively, the random resource combination (RC) input into this construction operation can be expressed as follows:

$$\begin{pmatrix} RC^1 \\ RC^2 \\ \vdots \\ RC^x \end{pmatrix} = \begin{bmatrix} C_1^1 & C_2^1 & \cdots & C_i^1 & E_1^1 & E_2^1 & \cdots & E_i^1 \\ C_1^2 & C_2^2 & \cdots & C_i^2 & E_1^2 & E_2^2 & \cdots & E_i^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ C_1^x & C_2^x & \cdots & C_i^x & E_1^x & E_2^x & \cdots & E_i^x \end{bmatrix}, \quad (4)$$

where RC^x = the xth random RC; C_i^x = the xth random crew number of activity i; and E_i^x = the xth random equipment number of activity i. If it is assumed that the cycle time (CT_{ij}) expressed in Eqn (1) is a functional formula f(x) and "x" of random RCs (RC^x) in Eqn (4) are inputted to $f(x)$, the duration changes due to the change in the resource quantity in each activity, moreover which results in a change in the start and complete time of each activity. Finally, the three variables (EST, duration, and float time) in Eqn (1) change. Thus, the cycle time at that point is calculated as follows:

$$f\begin{pmatrix} RC^1 \\ RC^2 \\ \vdots \\ RC^x \end{pmatrix} = \begin{bmatrix} CT^1 \\ CT^2 \\ \vdots \\ CT^x \end{bmatrix}, \quad (5)$$

where CT^x = cycle time by the xth random RC.

If one of the RCs, RC^k, shows the minimum cycle time value among the various CT^x values produced by Eqn (5), it turns out that the RC RC^k makes not only the flow of work on each zone smooth, but also a float time minimized. Therefore, the minimum value of cycle time and the equivalent RC could be the "optimal solution" to which efficient space zoning is applied.

3. Model application

3.1. Case introduction

SCHEME was applied to the steel structure construction, where the space zoning concept is often attempted to reduce the construction duration of high-rise buildings. The case analyzed for the application of the model to the steel structure construction is a high-rise building with 67 floors and six underground floors, standing 263 m high and has a total area of 223,146 m^2. The building was completed in December 2003. The center of the building consists of steel-reinforced concrete core walls, and the steel structure method was used for the slave. As the shapes and amounts of the materials in all the zones were very similar to one another, as shown in Table 1, the space zoning for the steel structure construction was planned to three zones per floor. The construction was composed of three activities (i.e. activity 1: column erection; activity 2: girder and beam installation; activity 3: deck plate installation), and they were iterated in each segmental zone as well as each floor. On the steel structure construction of the high-rise building analyzed, column erection, one of the three activities, was not constructed floor-by-floor; as in those constructions of a normal high-rise building, but

Table 1. Case introduction

		Quantity			
Space zoning	Activity	Zone 1 (pcs)	Zone 2 (pcs)	Zone 3 (pcs)	Average weight (ton)
Zone 1	Column erection	10	9	9	4.75
Zone 2	Girder/ beam install	15/23	15/26	16/36	0.68/0.43
Zone 3	Deckplate install	9	10	11	0.42

constructed by "tiers (i.e. sets of three or four floors each)." Moreover, based on these erected columns, activity 2 (i.e. girder/beam installation) and activity 3 (i.e. deck plate installation) were performed. From the ground level, the analyzed building consists of a total of 24 tiers, from which 21 data-sets (i.e. 21 cases in Table 2) with similar sizes could be collected for this study. Using these data-sets, the durations of the COMBI and NORMAL elements, which constitute the model, were calculated, and the number of input resources was determined.

3.2. Development of SCHEME for steel structure construction

Based on Fig. 3, SCHEME for steel structure construction, as shown in Fig. 4, was developed in this study, using the results of the case study. Since the analyzed case had three divided zones, three zone resources were defined in node 1, as shown in Fig. 4. The case analysis result shows that two crew were allotted to each activity on average (i.e. one crew for installation and one for bolting or welding), as described in nodes 4, 12, and 18, respectively. Meanwhile, lifting of the materials (i.e. column, girder/beam, and deck plate) to be inputted in the analyzed case was performed at night, to reduce the work load of a tower crane and avoid work interference from a tower crane. Moreover, since the cycle time of the steel structure construction process in the case study was calculated based on nine hours working per day, the lifting process was not included in the model in Fig. 4.

For the model developed to represent the condition of the actual site effectively, it is very important to clearly define the duration of each activity (AbouRizk *et al*. 1994; Halpin, Riggs 1992). As shown in Table 2 which shows (1) the most likely duration for conducting each activity on one zone; and (2) cycle time for finishing a steel construction work per one tier (i.e. time during which all activities are iterated three times), column erection (node 2) is average to consume 7.52 hours while girder/beam installation (node 10) and deckplate installation (node 20) are average to consume 7.74 and 5.39 hours, respectively. Using these data-sets, the durations of nodes 2, 10, and 20 were calculated. In other words, once the distribution of 21 data-sets was analyzed using the result of the analysis, the duration of each activity was calculated based on triangular distribution. Triangular distribution is not largely affected by the number of sample data, and its calculation method is simple, thereby making data collection easy and accurate (Back *et al*. 2000; Moder *et al.* 1983; Hong *et al*. 2011; Hong, Hastak 2007). For example, Table 3 shows the duration data-set for simulating the case 2 in Table 2. Since the stochastic method cannot be used to calculate the transition time

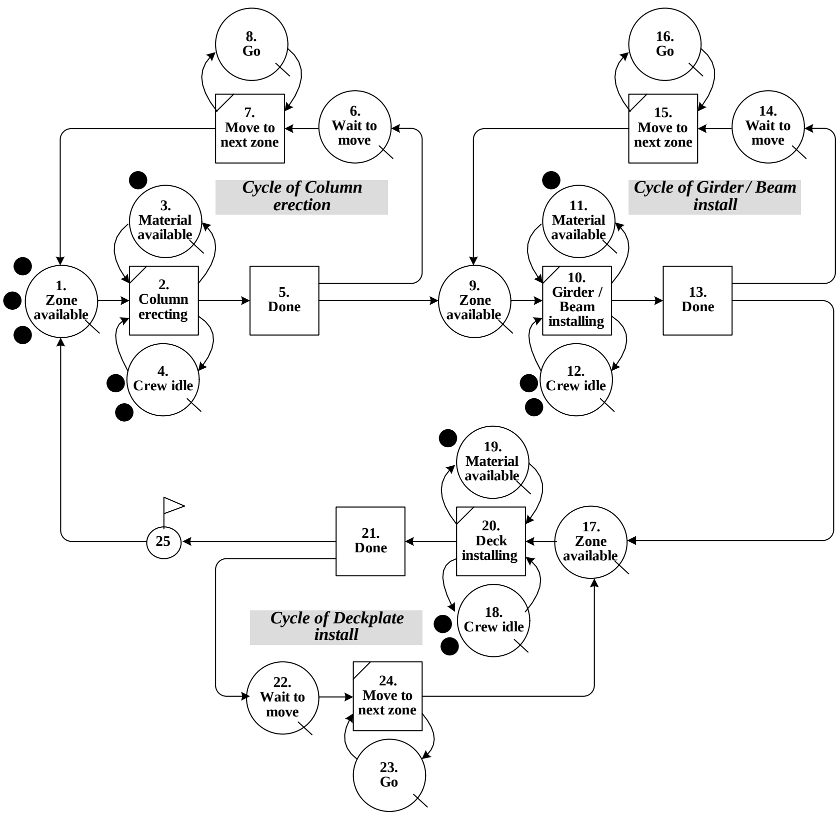

Fig. 4. SCHEME for steel structure construction

Table 2. Report of actual data-set and simulation results

Case	Data-sets of actual case: Column erection[a] (node 2)	Girder/beam installation[a] (node 10)	Deckplate installation[a] (node 20)	Cycle time (a)[b]	Simulation results (b)[c]	Difference ($a-b$)	Percentage of difference [$(a-b)/a \times 100$]
Case 1	6.41	5.34	6.01	30.77	29.80	0.97	3.14
Case 2	7.01	5.70	4.02	28.13	25.01	3.12	11.09
Case 3	6.10	6.36	4.02	25.04	24.08	0.96	3.83
Case 4	9.43	7.57	4.43	36.59	35.00	1.59	4.34
Case 5	9.50	11.27	5.76	52.61	52.43	0.18	0.34
Case 6	6.86	6.10	4.79	29.95	28.30	1.65	5.51
Case 7	8.07	5.72	4.34	29.56	27.40	2.16	7.31
Case 8	6.44	9.76	4.36	46.72	42.12	4.60	9.85
Case 9	9.41	6.58	4.86	34.02	30.90	3.12	9.18
Case 10	6.38	5.52	7.48	34.32	34.30	0.02	0.07
Case 11	6.70	6.46	5.03	31.10	28.60	2.50	8.04
Case 12	8.47	7.18	6.04	36.05	34.10	1.95	5.42
Case 13	6.18	6.18	7.70	35.97	35.50	0.47	1.31
Case 14	6.51	6.45	5.03	30.90	28.40	2.50	8.10
Case 15	7.35	5.52	5.03	28.94	28.30	0.64	2.22
Case 16	10.01	8.81	5.00	41.43	40.30	1.13	2.73
Case 17	6.13	7.23	6.75	36.75	34.20	2.55	6.93
Case 18	5.79	10.43	6.84	53.20	47.34	5.86	11.02
Case 19	7.33	10.48	5.86	50.94	47.66	3.28	6.45
Case 20	7.68	10.50	4.79	49.60	43.99	5.61	11.30
Case 21	10.18	13.31	5.10	61.46	55.21	6.25	10.16
Average	7.52	7.74	5.39	38.29	35.85	2.44	6.11

[a]Most likely durations for constructing each activity on one zone.
[b]Construction times during which all activities are iterated three times.
[c]Simulation times using the developed model based on actual data-set.

from one zone to the next (i.e. nodes 7, 15, and 24), the deterministic value based on the interviews with field managers was used instead. As described earlier, since nodes 5, 13, and 21 were dummy nodes set for the precedence relationship of the model, the duration of these dummy nodes was set to a minimum (i.e. 0.0001 hour) so it would not affect the actual total cycle time.

3.3. Model validation

It is crucial to examine whether the model developed reflects the actual steel structure construction well. Thus, the model was verified based on two aspects. First, whether the process of model using space zoning concept and the one of actual construction can run identically or not was examined by chronologically analyzing the events that had been completed during the simulation operation. Second, the cycle time resulting from the simulation of the developed model was compared to the cycle time from the actual case.

3.3.1. Chronological list

Fig. 5 shows the simulation result from the developed model based on actual case 2 (i.e. data-set in Table 3), in terms of completing steel construction work on one

Table 3. Duration input data of case 2 for simulation

Node no.	Name	Duration (hours)[a]: Minimum	Most likely	Maximum	Remark
2	Column erection	5.21	7.01	8.31	Work node
10	Girder/beam installation	4.23	5.70	7.12	
20	Deckplate installation	3.71	4.02	5.23	
7, 15, 24	Move to next zone		0.3[b]		
5, 13, 21	Done		0.0001[b]		Dummy node[c]

[a]Durations for constructing each activity on one zone.
[b]Deterministic value by experts of the analyzed case.
[c]Node for modeling the logical relationship.

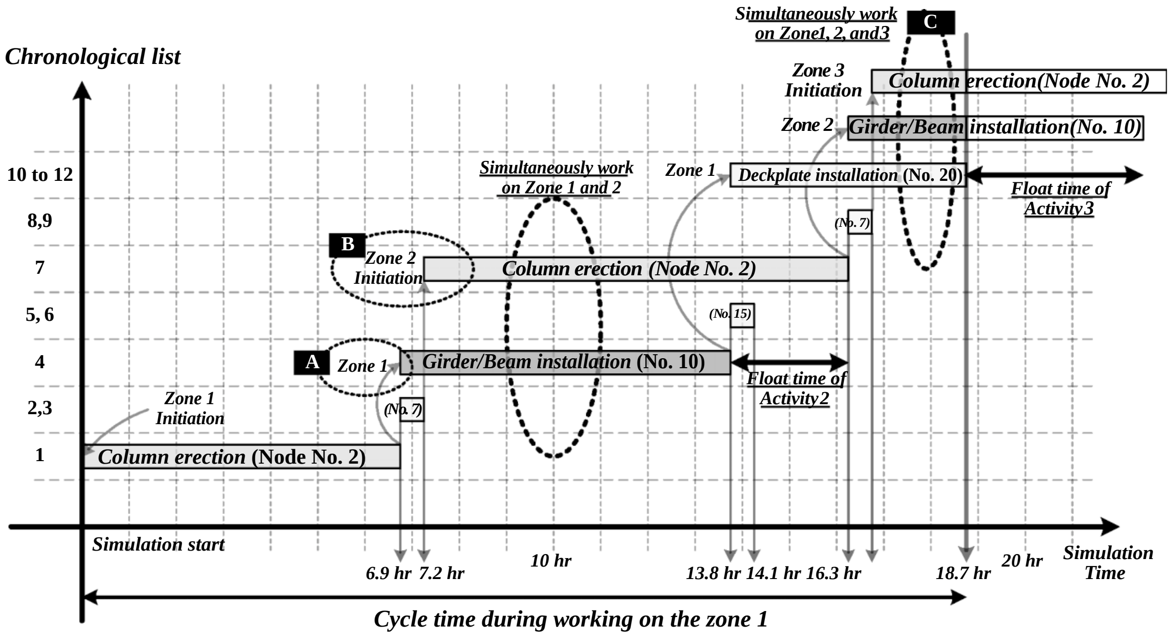

Fig. 5. Chronological lists by simulation

zone. Fig. 5 chronologically listed the events that were completed during the simulation, in terms of the COMBI (i.e. nodes 2, 7, 10, 15, 20, and 24) and NORMAL (i.e. nodes 5, 13, and 21) elements with defined durations. Through the analysis of the initiation and completion of the events, it was examined whether the operation of the developed SCHEME is identical to the actual work process. The key events in chronological order are as follows:

(1) Works on zone 1: as shown in Fig. 5, once the simulation started, "column erection (node 2)" was working on zone 1 until 6.9 hours (i.e. *chronological list 1*), and then "girder/beam installation (node 10)" continuously was proceeding until 13.8 hours (i.e. *chronological list 4*), as shown in "A" in Fig. 5. Thereafter, "deck plate installation (node 20)" was working on zone 1 until 18.7 hours (i.e. *chronological list 10–12*);

(2) Works on zone 2: after "column erection (node 2)" finished on zone 1, that work was initiated on zone 2 at 7.2 hours (i.e. *chronological list 7*), as shown in "B" in Fig. 5. Then "girder/beam installation (node 10)" began on zone 2 at 16.3 hours (i.e. *chronological list 10–12*);

(3) Works on zone 3: after "column erection (node 2)" finished on zone 2, that work on zone 3 started at 16.6 hours (i.e. *chronological list 10–12*). As shown in "C" in Fig. 5, during the time from 16.6 hours to 18.7 hours, all three works were simultaneously working on zone 1, 2, and 3, respectively;

(4) Movement between each zone: once "column erection (node 2)" finished, the labor for column erection was moving from zone 1 to zone 2 until 7.2 hours (i.e. *chronological list 2 and 3*). And this labor crew started to move from zone 2 to zone 3 at 16.3 hours, after finishing the column erection at zone 2 (i.e. *chronological list 8 and 9*). Likely, the labor for girder/beam installation moved from zone 1 to zone 2 at 13.8 hours (i.e. *chronological list 5 and 6*).

The simulation results clearly demonstrate that in terms of iteration and overlapping, the work process of the developed model has been identical with the work process using space zoning, as shown in Figures 1 and 2. Furthermore, it can be verified that the developed model runs identically with the work process of the actual case.

3.3.2. Comparison between the actual data and the simulation result

Based on the previously collected 21 data-sets, the reliability of the developed model was verified by comparing: (1) the cycle time of actual case, and (2) the simulation result from the developed model, in terms of cycle time for finishing a steel construction work on each tier. Since there is no need to estimate the optimized cycle time in the process of comparing two values, the process explained in Eqns (4) and (5) was not performed. As shown in Table 2 and Fig. 6, the average value of the actual working cycle time was 38.29 hours, while the average cycle time from

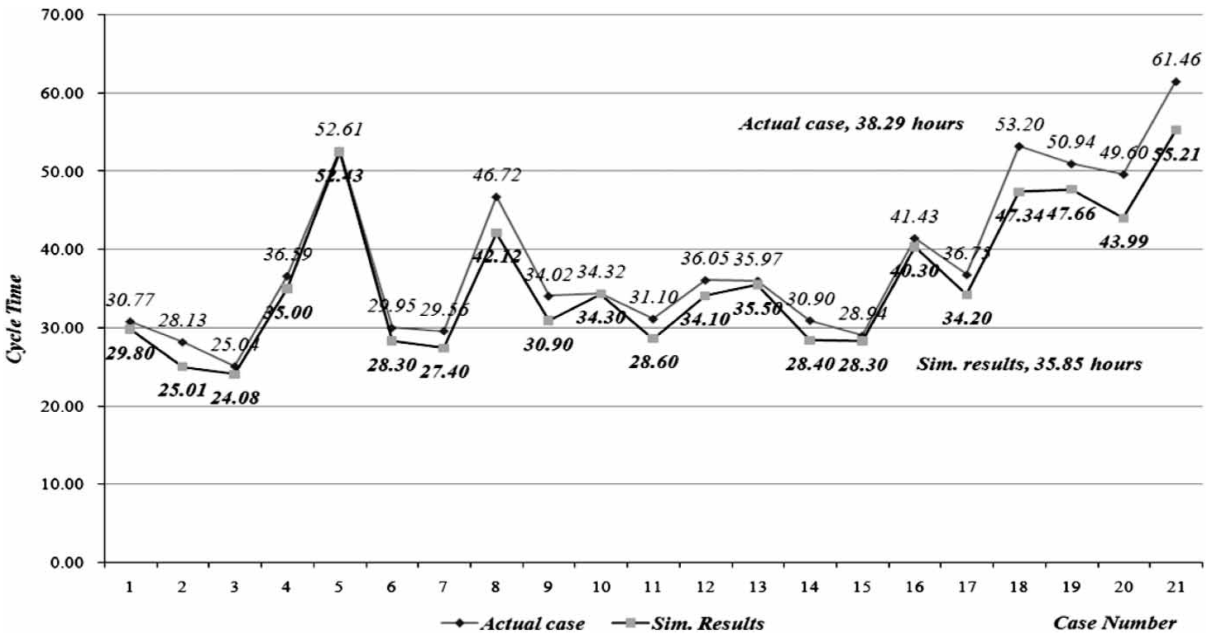

Fig. 6. Comparison between actual case and simulation result

simulation result was 35.85 hours. The comparison of the cycle time of the actual case and the cycle time estimated by the model showed that (1) the average difference between the two values was 2.44 hours, and (2) the average prediction power of the developed model was 93.89% (i.e. 93.89 = 100–6.11, refer to Table 2). Therefore, it is determined that the developed model predicts actual situations well. In addition, generally since the inputted resources in the simulation model were distributed ideally as the simulation progressed, the duration by the simulation model became smaller than that in the actual case (Halpin, Riggs 1992; Van Slyke 1963). As shown in Table 2 and Fig. 6, it turns out that the simulation results are smaller than the values from the actual case. Finally, these comparisons reveal that the model developed in this study is shown to be reliable.

3.4. Optimizing cycle time

The developed model can easily predict the construction duration and present the optimal cycle time with variations in input resources. Table 4 shows, for example, the explanation based on case 2 of Table 2 and 3. To calculate the optimal cycle time, which was explained mainly by Eqns (4) and (5), the variation scope of the crew resources that were inputted into the developed model was set to 1–5. Meanwhile, with respect to reflecting the condition of the actual case, the number of zones was fixed to three zones while examining the change in duration based on the change in the crew resources. Since the variation scope of each crew was set from 1 to 5, a total of 125 RCs [i.e. *RC* in Eqns (4) and (5)] could be produced (i.e. $125 = 5 \times 5 \times 5$). Shown in Table 4 is the result of

Table 4. Case introduction

RC* No	No. of crew 1**	No. of crew 2**	No. of crew 3**	Cycle time
1	1	1	1	24.0529
2	1	1	2	24.9532
3	1	1	3	24.5549
:	:	:	:	:
47	2	5	2	25.2685
48	2	5	3	23.5017
49	2	5	4	25.6246
:	:	:	:	:
123	5	5	3	25.6410
124	5	5	4	25.5755
125	5	5	5	26.1438

Note: * RC = Resource Combination
** Crew 1, 2, and 3 represent the crew of activity 1, 2, and 3, respectively.

the examination of how duration changed according to 125 *RC*s. The result shows that the optimal duration at the 48th *RC* was 23.5017 hours. Once the developed model is implemented, the cycle time could be mainly determined by durations for each work and idle time for each labor crew. This aspect does not guarantee that the more resource is used, the less cycle time is, because it would be possible to yield more idle time by more resource. This principle can address how the 48th *RC* could be selected as an optimal solution, even though the resource amount of the 48th *RC* is lower than one of 125th *RC*. Therefore, when two crews in activity 1, five crews in activity 2, and three crews in activity 3 were distributed in the analyzed steel structure construction case, the most efficient construction in terms of duration could be undertaken.

3.5. Effect of model application

To observe the effect of the model application, the model was examined in terms of the cycle time for constructing one floor. Based on the other steel structure construction case, the differences in cycle time in two cases were analyzed: when space zoning was applied to the work, and when it was not. The analyzed case was an office building with 30 stories from the ground, on which space zoning was not applied. From 22 floors with similar amounts of work, the 22 data-sets including the input resource and duration of the steel structure construction per floor were collected. Moreover, based on the conditions of the analyzed case (i.e. activity duration and resource input quantity), the model in Fig. 4 was revised, and the simulation results and the actual cases were compared.

Shown in Fig. 7 is the result of the comparison. The average duration of the construction of one floor in the actual case was 53.07 hours. When space zoning was applied to the case with identical conditions (i.e. the simulation results), the average duration of the construction of one floor was 31.92 hours. Therefore, it was determined that space zoning reduced the construction duration of one floor by 39.84% (39.84 = (53.07 − 31.92)/53.07) on average. This indicates that it is effective for a project manager to perform space zoning using the developed model.

Conclusions

Many researchers have studied efficient space zoning to reduce the construction duration and interference among the different construction works. These studies, however, were dependent on the network-based scheduling methods using the space zoning concept in attempting to reduce the construction duration, making it difficult to reflect "iteration" and "overlapping," the two characteristics of space zoning. This study was conducted for the purpose of developing a scheduling model using the space zoning concept, to overcome the limitations of the existed studies and to reduce the construction duration by maximizing productivity. Using CYCLONE, one of the popular discrete-event simulation methods, SCHEME was developed in this study, which was then used to come up with a simulation of steel structure construction, a representative construction operation in which space zoning was often applied. It was shown that the developed model reflects the characteristics of the actual construction processes where space zoning is used (i.e. iteration and overlapping), and that the simulation time for completing the steel structure construction work is similar to that in the actual case. It was also shown that applying the developed model to space zoning results in superior performance in terms of the reduction of construction duration in cases with no

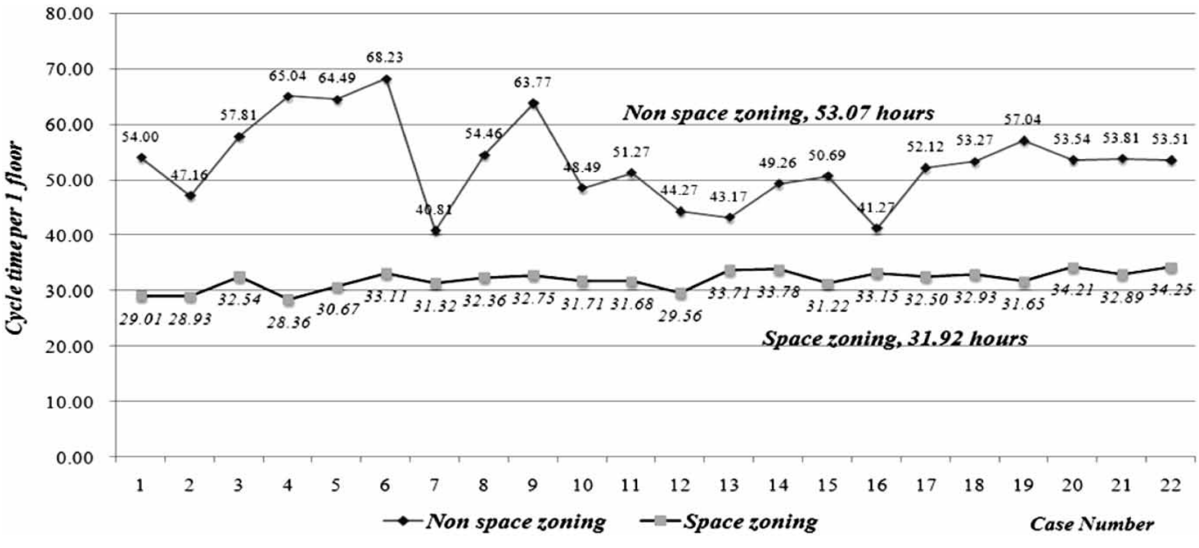

Fig. 7. Comparison between nonspace zoning and space zoning

space zoning. There are main contributions of the developed model: (1) from the academic point of view, the input resource-based model was developed for repetitive construction works using space zoning to easily estimate and reduce the project duration. The established model enables flexible expansion according to the zoning plan of the working space and the type of activities. Moreover, the proposed model was developed with proper consideration of uncertainty, and thus, can produce more reliable estimations; (2) from the practical point of view, the application of the developed model allows (i) easy updates of the duration based on the changes of construction conditions, and (ii) smooth management of the project because the user can easily recognize the effect of the changes of resources inputted to each work on the duration. Therefore, it is expected that SCHEME will yield excellent results in repetitive construction operations in actual construction projects in terms of productivity and construction duration.

It should be noted, however, that this study considered only the construction duration in performing space zoning and in presenting the optimal cycle time. Therefore, for more efficient space zoning in construction projects, further studies considering cost aspects should be conducted in the future. Moreover, since space zoning should yield both congestion in construction phase and difficulty in planning, the developed model in this paper is not sure of successful space zoning implementation. Therefore, further research to ensure the high engineering and construction management skills for achieving the successful space zoning implementation is necessary.

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