Evaluation of Lifting Efficiency of Double-Cage Construction Lift in Supertall Building Construction

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Abstract

Construction lifts are key equipment used in the vertical transportation of resources in supertall building construction. Also, according to the increase of vertical lifting distance, construction lifts are becoming more important for successful projects completion. However, a limited number of construction lifts were hard to handle the lifting load during peak-time in which the construction resources are concentrated. Also, a large number of stops caused a decrease of lifting efficiency. Consequently, these problems cause an increase of lifting time of the resources and construction delay can occur. Therefore, it is necessary to apply concept of double-deck elevators to construction lift in order to decrease the lifting time of the resources. In this study, two discrete event simulation models using the CYCLONE are developed to evaluate the lifting time of workers, who are required to be located on the upper floor workplace in the morning peak-time. Also, comparative analysis of lifting efficiency between single-cage lift and double-cage lift is conducted. As a result, the proposed simulation model of double-cage lift shows a remarkable decrease of 38.0% compared with single-cage lift. This result could contribute to set the direction of development for double-cage lift. Furthermore, it is expected to support construction manager to find optimal hoisting plan with minimum lifting time in supertall building construction.

Keywords –

Double-cage; Construction Lift; Supertall Building; Lifting Efficiency; Discrete Event Simulation; CYCLONE

1 Introduction

1.1 Background and Objective

As the number of supertall buildings has been increased recently, the heights of buildings have consistently been getting higher[1]. Vertical lifting distance of construction resources, such as material, equipment and labor, has been also getting longer. Thus, the construction lift, which is one of the key lifting facilities, is becoming more important for successful project completion[2].

In supertall building construction, a limited number of construction lifts should move amount of construction resources up to working area on high floors[3], and it cannot afford the vertical loads during peak-time in which the resources are concentrated. This problem can cause an increase of lifting time and construction delay. In the case of the Korea Convention and Exhibition Center, during the peak-time when workers arrive in the morning, it took about 130 minutes to lift 1,200 workers to their work floors[4]. Also, in case of the Burj Kalifa construction project in Dubai, it took approximately 45 minutes as one cycle to transport workers from ground floor to the top floor by using the three-stage lift system [4]. These cases indicate an improvement of lifting efficiency, that is vertical transport capacity of workers at the same time, can shorten the construction time through the reduction of lifting time in whole project's period.

Meanwhile, in the elevator industry, double-deck elevators, each comprising two connected cars that move simultaneously in the same vertical shaft, are developed to reduce the total number of needed elevators and also to minimize the number of stops[5,6]. This elevator has twice the amount of transport capacity compared with single-deck elevator and decreases passenger's waiting time, which insinuates increase in lifting efficiency[7]. Therefore, it is necessary to apply the concept of double-deck elevators to construction lift, in order to save the lifting time of workers.

The aim of this study is to evaluate lifting efficiency between single-cage lift and double-cage lift which is comprised two cages, one located above the other, by calculating lifting time of workers using the discrete event simulation. The result of this research could contribute to setting the direction of double-cage lift's development. Furthermore, it is expected to be utilized for supporting construction manager to make efficient planning of the lifting equipment in supertall buildings construction.

1.2 Research scope and method

Research scope is constrained to supertall buildings, over 100 floors, which is needed to improve lifting efficiency. Also, workers who are rising to work floors in the morning is included only in this study. Because traffic for lifting resources, especially in the number of workers, has been a sharp rise, at 06:30-8:00 am. And, high speed type of construction lift, which is generally applied in supertall building construction, is used in this study.

In this research, we develop a model for calculating worker's lifting time through lift operation process by using the CYCLONE (Cyclic Operation Network) which is given in Halpin(1973). Two simulation models are developed, one for single-cage lift under unlimited operation and the other for double-cage lift under skip operation suitable for peak-time with the maximum lifting load, for comparison of lifting efficiency

2 Literature review

2.1 Research Trend of Construction Lift

Supertall building construction utilized lifts for the vertical transportation of resources, including labor and relatively small materials. This section introduces some related research about construction lift.

Ahn presents a process of a vertical movement plan for labors to improve lifting efficiency of construction using discrete event simulation[3]. Kim et al. suggested the estimation process of proper numbers of construction lifts[14]. Shin et al. proposed a simulation model incorporating genetic algorithms for supporting hoist planners to make an optimal plan with minimal time and effort for high-rise building construction[17]. Moon et al. studied method of optimizing a transfer floor for workers during the morning peak time by using discrete event simulation[18]. Most researches for vertical movement focused on the lifting management rather than development of new equipment for lifting efficiency.

2.2 Types of Double-Cage Lift Operations

Operation types of double-cage lifts are divided into skip operation, restricted operation and unlimited operation. Conceptual diagram is illustrated in Figure 1.

Firstly, skip operation's regulation is the upper cage stops at even number floors and the lower cage stops at odd number floors. Secondly, restricted operation's regulation is registration of target floors by people boarding at the ground floor is restricted to only even number floors for the upper cage and only odd number floors for the lower cage. However, no restrictions apply to workers boarding at other floors. Lastly, unlimited operation regulation is to put in a lift call to any floors.

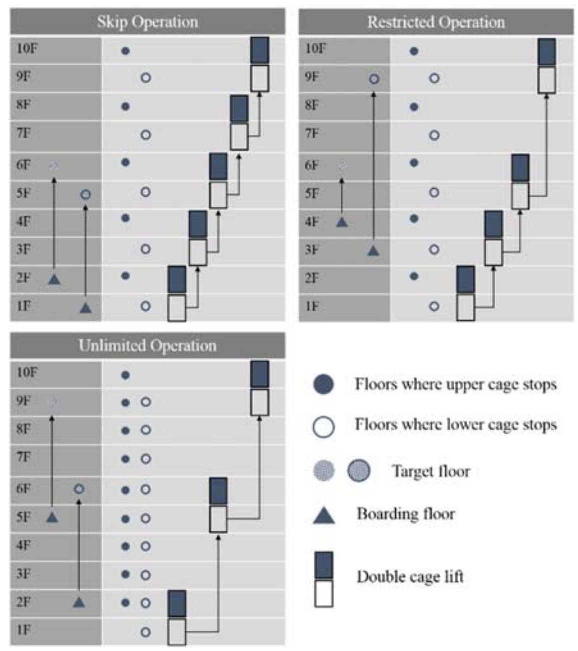


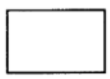
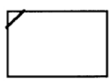
Figure 1. Three Operation Types of Double-Cage Lift

2.3 CYCLONE

The CYCLONE system approach was developed in the early 1970s. This system showed the potential for modeling and simulation of repetitive construction processes. In 1987, Lluch and Halpin further developed the microcomputer version of CYCLONE named MicroCYCLONE[10].

CYCLONE is the most suitable method to measure the actual productivity considering the relationship with resources, duration and work task. The CYCLONE simulation model can provide the actual construction situation simply for the construction engineers to occur problems in construction process. Also, it suggests to derive improvement way which is efficient work process[10]. Table 2 shows CYCLONE modeling elements.

Table 1. CYCLONE Modeling Elements
(Halpin and Riggs 1992; Han et al. 2010)

Symbol	Name	Description
	NORMAL	Unconstrained in its starting logic and indicates active processing of (or by) resource entities
	COMBI	Logically constrained in its starting logic, otherwise similar to the NORMAL work task modelling element
	QUEUE	Represents a queuing up, or waiting for the use of passive state resources
	COUNTER	Counts the number of times a key unit passes a particular control point in the network model so that production can be measured
	ARC	Used to model the direction of resource entity flow between the various active-state nodes and the passive-state nodes

3 Simulation Model for Evaluation of Lifting Efficiency

3.1 Operation Process of Construction Lift

Operation process of a construction lift was analyzed in order to establish the simulation model of single-cage lift and double-cage lift. This process begins with the preparation of lifting such as opening door by crew, getting on a lift for workers and closing door by the crew in the ground floor. When its preparation is finished, the construction lift will be starting to move to target floors. And workers are getting off the construction lift which is arrived at target floor. Lastly, lift is descending toward the ground floor. This process is repeated until all workers who were waiting on the ground floor arrive at target floor.

In this research, operation process of construction lift was simply classified into 10 steps, and Table 3 represent it.

Table 2. Operation Process of Construction Lift

Step	Work task	
1	Door opening (ground floor)	Safety door opening
		Lift door opening
2	Getting on the lift (workers)	
3	Door closing (ground floor)	Lift door closing
		Safety door closing
4	Moving to target floor (lift)	
5	Arrival at target floor (lift)	
6	Door opening (Target floor)	Lift door opening
		Footboard lowering
		Safety door opening
7	Getting off the lift (workers)	
8	Door closing (Target floor)	Safety door closing
		Footboard putting
		Lift door closing
9	Moving to ground floor (lift)	
10	Arrival at ground floor (lift)	

3.2 Calculation Method of Hoisting Time

To derive a result from the simulation model, hoisting time of construction lift should be calculated on every travels between ground floor and target floor. For a more accurate estimation of the hoisting time, this study adopted calculation method considering acceleration and deceleration, suggested by Cho et al.[12]. Also, we utilized the acceleration and deceleration time of single-cage lift which was provided by Cho et al.[13]. And we identified the acceleration and deceleration time of double-cage lift by interviewing with the hoist manufacturer who is developed the double-cage lift. Table 4 represents the acceleration and deceleration time of lift

Table 3. Acceleration/Deceleration Time of Lift

	Constant Velocity (m/min, m/sec)	Acceleration time (sec)	Deceleration time (sec)
Single-Cage Lift	100, 1.67	5.5	2.8
Double-Cage Lift	80, 1.33	4.5	4.0

Lifting time(T_m) can be calculated by the sum of lifting time at constant velocity(T_{cv}), acceleration time(S_1), and deceleration time(S_2) (see Equation (1)).

T_{cv} is the sum of the lifting time after the acceleration section, reached to top of the first floor(T_{v1}), the lifting time from bottom of (n-1)floor to starting point of deceleration($T_{v(n-1)}$), and the lifting time of the rest of all at constant velocity(T_v) (see Equation (2),(3)). For the calculation of acceleration distance(h_1) and deceleration distance(h_2), we assumed that acceleration for reaching the constant velocity was uniform. Figure 3, Figure 4 shows velocity-time graph of lift operation.

$$T_m = T_{cv} + S_1 + S_2 \quad (1)$$

$$T_{cv} = T_v + T_{v1} + T_{v(n-1)} \quad (2)$$

$$T_{v1} = \frac{H_1 - h_1}{V}, T_{v(n-1)} = \frac{H_{n-1} - h_2}{V}, T_v = \frac{\sum_{i=2}^{n-2} H_i}{V} \quad (3)$$

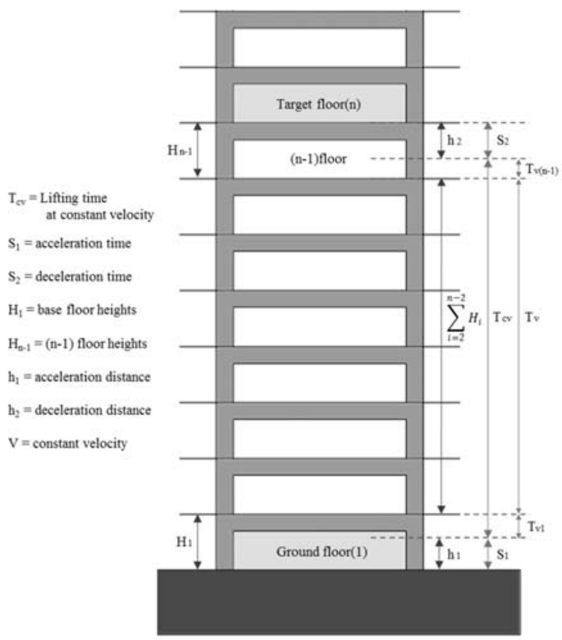


Figure 2. Basic Model for Calculation of Hoisting Time (Cho et al. 2010)

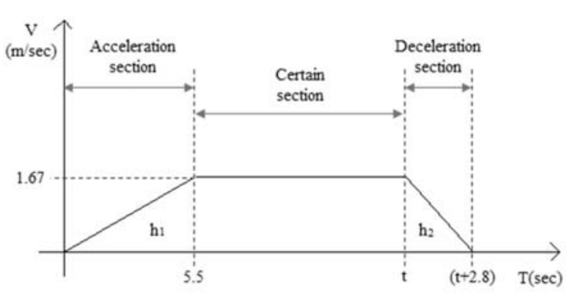


Figure 3. Graph of Single-Cage Lift Operation

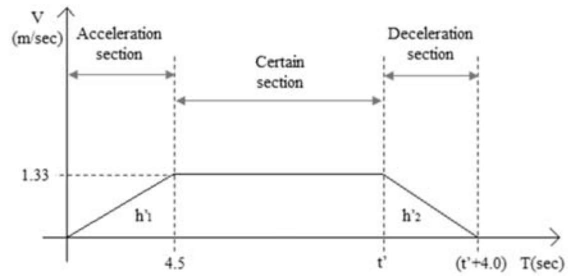


Figure 4. Graph of Double-Cage Lift Operation

3.3 Simulation

3.3.1 Assumptions for Simulation

In this research, some conditions were assumed to estimate the lifting time of workers. The assumptions are described as follows;

1. All workers(1,200) arrive at the construction site simultaneously in the morning, and they are waiting for lifting.
2. Every worker was assumed that weight is 80kg and volume is $0.2m^2$. And we determined the maximum number of boarding workers in the cage to select smaller between calculation by weight and calculation by volume.
3. Performance of the cage(size:1.5m * 4.5m * 2.65m, capacity:3,000kg) is same. However the maximum capacity of double-cage lift is set 2,500kg each, considering safety of lift operation.
4. The number of single-cage lift and double-cage lift is one each.
5. Workers are always getting on a lift at ground floor, and they are getting off the lift at 122^{nd} floor, 123^{rd} floor only.
6. The required number of workers on 1^{st} target floor(122^{nd} floor) and 2^{nd} target floor(123^{rd} floor) are assumed 600 workers each.
7. The height of each floor is 3.5m.
8. The sum of workers cannot exceed the maximum number of boarding workers for safety.
9. Lift always operates normally, and any unexpected malfunction was excluded.

Simulation conditions are shown in table 5.

3.3.2 Simulation Model for the Single-Cage Lift

Lifting workers by single-cage lift consisted of 10 work tasks as shown in the table 3. Work tasks were divided into two parts, one is from 'door opening(ground floor)' to 'arrive at target floor', the other is from 'door opening(target floor)' to 'arrive at ground floor'.

Table 4. Simulation Conditions

	Single-Cage Lift	Double-Cage Lift
Total Lifting workers	1,200	
Lift Capacity(kg)	3,000	5,000
Number of Lift	1	
Speed of Lift(m/s)	1.67	1.33
Boarding Floor	1	
1st Target Floor	122	
2nd Target Floor	123	
Floor Height(m)	3.5	

Simulation model for the single-cage lift using the CYCLONE is shown in Figure 5.

Resources which are input the simulation model are a single-cage lift, 3 operating crews who helped with the operating lift each floor, and 33 workers who are required to transport work floor. Table 6 is the details of resource of input data for single-cage lift.

Table 5. Resource of input data for Single-Cage Lift

Node	Work task	Resource	Amount of resource
2	Lift door opening (ground floor)	Operating crew	1 crew
		Single-Cage Lift	1 each
6	Getting on the lift	Worker	33 workers
11	Lift door opening (1st target floor)	Operating crew	1 crew
17	Lift door opening (2nd target floor)	Operating crew	1 crew

Finally, we have to set the duration of work tasks before running the simulation model. In order to get the duration information of 'lift door opening', 'getting on a lift', 'getting off the lift', 'lift door closing', interviews were conducted with engineers who were the experts of construction lift. And then, we input duration information of work tasks by using the uniform distribution. Also, lifting time was calculated by using the Equation (1,2,3), and it is defined as deterministic values. Table 7 is the details of duration of input data for single-cage lift.

Table 6. Duration of input data for Single-Cage Lift

Node	Work task	Value type	Duration (Second) Min	Duration (Second) Max
2	Lift door opening (ground floor)	Uniform	3	5
6	Getting on the lift	Uniform	16.5	49.5
8	Lift door closing (ground floor)	Uniform	3	5
9	Moving to 1st target floor	Deter-ministic	259.7	
11	Lift door opening (1st target floor)	Uniform	5	8
13	Getting off the lift	Uniform	8.5	25.5
14	Lift door closing (1st target floor)	Uniform	5	8
15	Moving to 2nd target floor	Deter-ministic	5.14	
17	Lift door opening (2nd target floor)	Uniform	5	8
19	Getting off the lift	Uniform	8	24
20	Lift door closing (2nd target floor)	Uniform	5	8
21	Moving to ground floor	Deter-ministic	261.9	

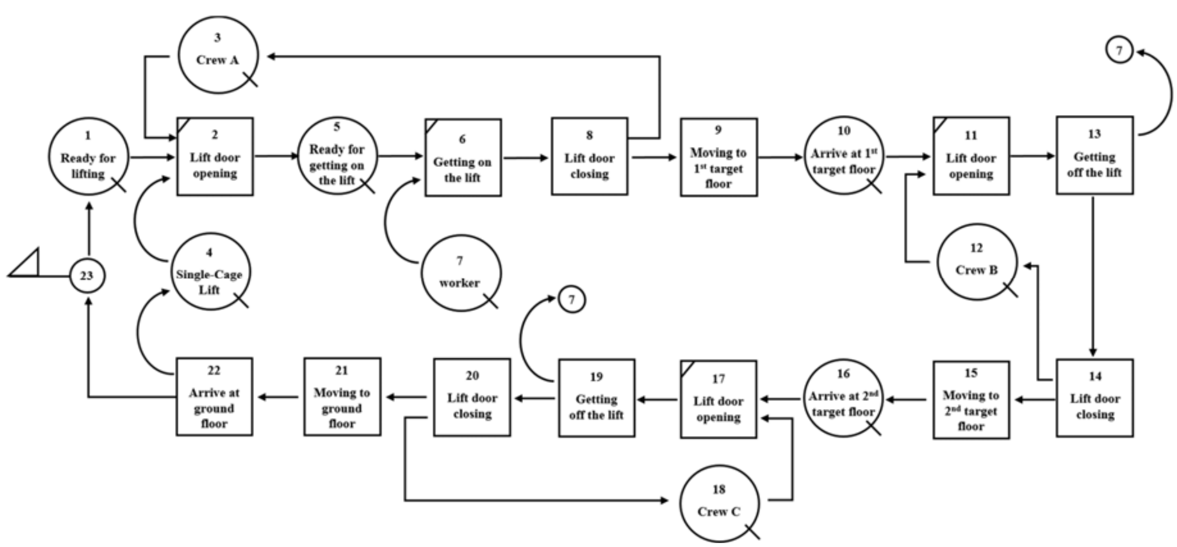


Figure 5. Simulation model for the Single-Cage Lift

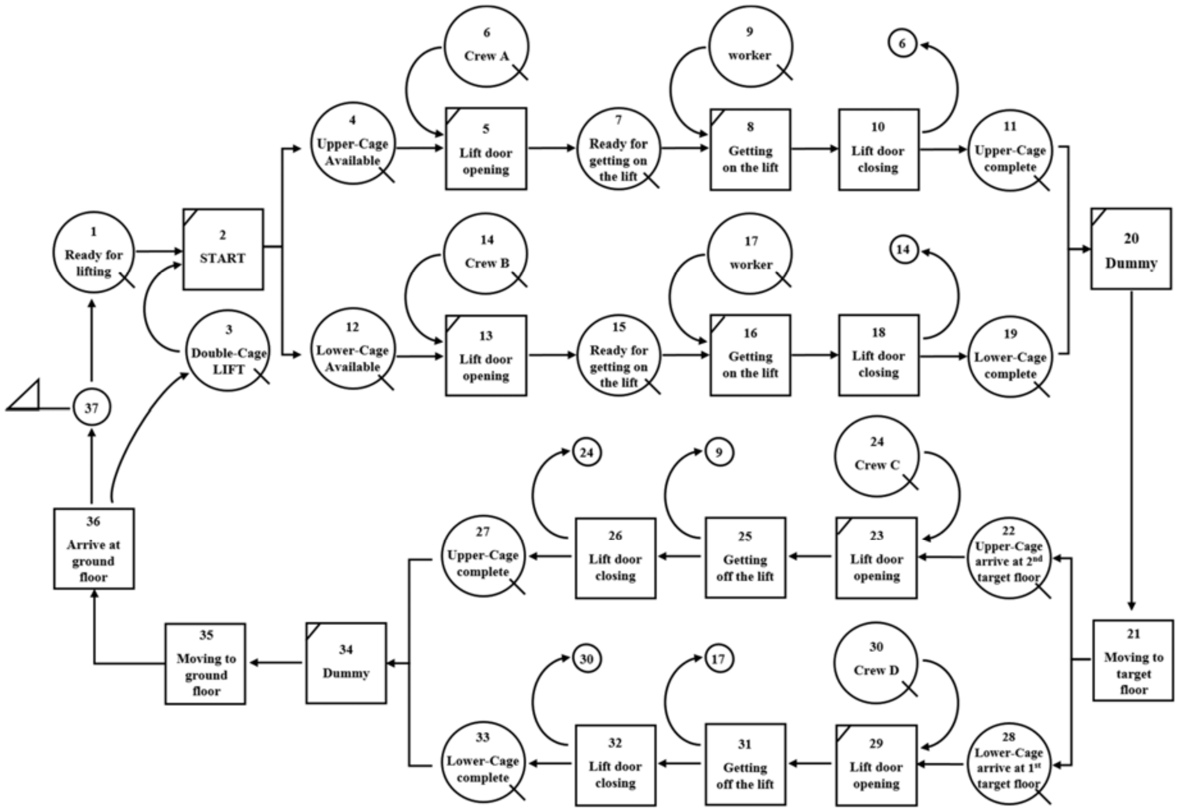


Figure 6. Simulation model for the Double-Cage Lift

3.3.3 Simulation Model for the Double-Cage Lift

Simulation model for the double-cage lift using the CYCLONE is shown in Figure 6. Operation process is very similar between single-cage lift and double-cage lift. However, due to make up with upper-cage and lower-cage in double-cage lift, several work tasks(eg. step 1,2,3,6,7,8 in Table 3) were progressed separately. At this time, when the work tasks of two cages are entirely finished before moving to other floor, it could be possible for work task to progress to the next step.

Resources which are input the simulation model are a double-cage lift, 4 operating crews who helped with the operating lift, and 62 workers who are required to transport work floor. Table 8 is the details of resource of input data for double-cage lift.

Duration of input data for double-cage lift is shown in Table 9. We utilized duration information of single-cage lift, since several work tasks of double-cage lift were similar with single-cage lift. However, lifting time and duration of getting on/off a lift are different by the number of boarding workers and speed of lift. So, we set the duration of them to suit condition of double-cage lift.

Table 7. Resource of input data for Double-Cage Lift

Node	Work task	Resource	Amount of resource
2	Start	Double-Cage Lift	1 each
5	Lift door opening (Upper-Cage/ Ground floor)	Operating crew	1 crew
8	Getting on the lift (Upper-Cage)	Worker	31 workers
13	Lift door opening (Lower-Cage/ Ground floor)	Operating crew	1 crew
16	Getting on the lift (Lower-Cage)	Worker	31 workers
23	Lift door opening (Upper-Cage/ 2nd target floor)	Operating crew	1 crew
29	Lift door opening (Lower-Cage/ 1st target floor)	Operating crew	1 crew

Table 8. Duration of input data for Double-Cage Lift

Node	Work task	Value type	Duration (Second)	
			Min	Max
5	Lift door opening (Upper-Cage/ Ground floor)	Uniform	3	5
8	Getting on a lift (Upper-Cage/ workers)	Uniform	15.5	46.5
10	Lift door closing (Upper-Cage/ Ground floor)	Uniform	3	5
13	Lift door opening (Lower-Cage/ Ground floor)	Uniform	3	5
16	Getting on a lift (Lower-Cage/ workers)	Uniform	15.5	46.5
18	Lift door closing (Lower-Cage/ Ground floor)	Uniform	3	5
21	Moving to target floor	Deter-ministic	319.4	
23	Lift door opening (Upper-Cage/ 2nd target floor)	Uniform	5	8
25	Getting off a lift (Upper-Cage/ workers)	Uniform	15.5	46.5
26	Lift door closing (Upper-Cage/ 2nd target floor)	Uniform	5	8
29	Lift door opening (Lower-Cage/ 1st target floor)	Uniform	5	8
31	Getting off a lift (Lower-Cage/ workers)	Uniform	15.5	46.5
32	Lift door closing (Lower-Cage/ 1st target floor)	Uniform	5	8
35	Moving to ground floor	Deter-ministic	319.4	

4 Results

Table 10 shows the results of single-cage lift simulation. In the simulation test, we conducted a simulation cycle 1,000 times to get more accurate results of cycle time. The total simulation time for 1,000 cycles was 174.19 hours and each cycle time of average was 10.45 minutes. Thus, the total number of lifting cycles required to reach for 1,200 workers to their designated work floors was 37 cycles and it took approximately 6.44 hours. Table 10 shows the results of double-cage lift simulation. Simulation model was carried out 1,000 times, and the total simulation time was 200.67 hours. Also, a cycle time of average was 12.04 minutes. Thus, the total number of repetition cycles to lift 1,200 workers to target floors was 20 cycles and it took about 4.01 hours.

As a result of the comparison, it was estimated that the lifting time of the double-cage lift would decrease by about 38.0% compared with the single-cage lift. The reasons of the reduction lifting time were not only an increase in lift capacity but also minimization of stops. Therefore, this result supports the lifting efficiency for the double-cage lift is better than the single-cage lift.

5 Conclusions and Further Studies

According to the recent increase in the height of tall buildings, more time is needed for the vertical lifting of resources in supertall construction. However, due to the limit of maximum capacity of lift, double-cage lift is demanded for supertall construction project. In this research, we have developed two simulation models for single-cage lift and double-cage lift to evaluate lifting efficiency by using the CYCLONE. The developed models showed comparison value in which lifting time of double-cage lift is more efficient than single-cage lift about 38.0% during the morning peak-time. The result of this study will be utilized for setting the direction of development for double-cage lift. Also, it is expected to support construction manager to make optimal plans with minimum lifting time in supertall building construction. Further studies will need to verify the lifting efficiency of double-cage lift comprehensively by considering production costs, operation types, the number of cages and combination of multiple lifts.

Table 9. Comparison of simulation results of single-cage lift and double-cage lift

	Total Simulation time (hour)	Number of Simulation (cycle)	Productivity (cycle/second)	Cycle Time of Average (min)	Number of Repetition Cycles, Total Lifting Time (cycle, hour)
Single-Cage Lift	174.19	1000	0.001594	10.45	37 , 6.44
Double-Cage Lift	200.67	1000	0.001384	12.04	20 , 4.01

Acknowledgement

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