Master of Science in Engineering

Simulation Model to Optimize Transfer Operation of Construction Lifts for Super High-rise Buildings

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Abstract

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Recently, the number of super high-rise building projects have been increased after recovering from international financial crisis. In super high-rise building project, vertical lifting is critical to overall project productivity, due to its limited number of lifting equipment. Also for projects which buildings' height are higher than 400m, transfer operation in lifting is inevitable because of lifts' maximum lifting height. In transfer operation, setting a transfer floor is essential for saving lifting time of resources.

In this research, using discrete event simulation modeling with AnyLogic 7.0 software, module of a single lift operation has been established, and with multiple modules, the simulation model of lift system with transfer operation has been built. Based on this model, optimization model for finding the optimal transfer floor has been built on OptQuest software, using the metaheuristic optimization method. By using this optimization model, the method of optimizing a transfer floor for workers during the morning peak time has been proposed.

Comparing to the result of the case which transfer floor is designated to the middle floor, setting optimized transfer floor significantly decreased the total lifting time of workers. Also patterns of the change of lifting time on the variation of transfer floors were presented through the analysis in the research.

By using proposed simulation and optimization tool, saving budget and time through increasing available working hour is expected.

Keywords: Construction Lift, Transfer Operation, Efficiency, Super High-rise Buildings, Transfer Floor, Optimization, Simulation

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Chapter 1. Introduction

1.1 Research Background and Objective

Recently multiple super high-rise building construction projects are in progress throughout the world. According to CTBUH (Council on Tall Buildings and Urban Habitat), 73 super high-rise buildings which are over 200 meters high were constructed in the year of 2013, and the number of projects is constantly increasing (CTBUH, 2014).

Such super high-rise building construction projects require increased vertical lifting travel distance compared to middle size building construction projects. Due to its limited number of lifting equipment, lifting plan in process management is very critical for lifting large number of workers and scale of materials to workplaces located on higher floors (Ahn, 2004).

Previous studies on lifting have mainly focused on all-floor operation (Jung, 2004; Kim, 2006; Shin, 2010; Han, 2012). However on super high-rise building construction site, lifting with all-floor operation only is restricted due to lift's maximum travel distance limit. In practice, lots of efforts have been made to increase the maximum travel distance limit of lifts on construction sites. Despite of these efforts, frequent power cable damages and sudden voltage drops happen on site which result to delays on construction periods. In the case of Burj Kalifa construction project in Dubai, lifts of 400 meter maximum travel distance were used, but the constructor could not avoid frequent power cable damages, and experienced a serious delay on the project's period (Cho, 2010).

Considering the fact that the maximum vertical travel distance of lifts produced in Korea is 400 meters[1], lifting with transfer operation is required for super high-rise building construction projects which have over 100 floors. Through lifting system with transfer operation, travel distance of each lifts could be decreased and the efficiency of lifting operation can be raised.

During the early stage of vertical lifting planning, setting the transfer floor is critical for carrying out the optimal performance of lifting with transfer operation. However there are few cases of using transfer operation on lifting, so it is difficult to refer to other project cases. Furthermore since each construction sites require different amount of resources which need to be vertically lifted, setting optimal transfer floor for each construction projects is not easy. In studies on elevator traffic planning, which have many similarities with lift planning of construction sites, simulation methodologies have been utilized for analyzing the optimal variables for the efficiency of elevator operations (Ioannou and Martinez, 2006). Since lifting with transfer operation have multiple variables like elevator operation, using simulation methodologies for the optimization of transfer floor could be a good approach.

The purposes of this study are to establish the model of vertical lifting of workers with transfer operation, and to analyze the optimal transfer floor. Through the execution of simulation and the search of optimal value, this study aims to find out the optimal transfer floor for each number of top floors, and to derive the pattern of workers' average lifting time change with the variation of transfer floor. The result of this study may be used as a reference of decision

[1] Source : LiftTec Webpage (http://www.liftec.co.kr)

making for setting the transfer floor of establishing lift planning with transfer operation on super high-rise construction projects.

1.2 Research Scope and Methodologies

In this research, scope is constrained to buildings with heights of between 100 to 200 floors, which must require transfer operation on vertical lifting. Among resources which need vertical lifting, only workers' vertical lifting is included on the study, and time of analysis is the peak time when workers arrive in the morning, which have the maximum lifting load. Elevators which are installed during the construction period is excluded on this research. Horizontal travel of workers is not considered. Operation period is set to be a finishing work period, which the maximum number of workers are required.

Since it requires a large amount of costs and time for carrying out experiments on construction lifting system in real scale, it is suitable to use a simulation tool for assessing the problem of this research. Simulation is a tool for establishing the system which can meet the needs of forecast or experiment on models which reflect the real world, under various environments and conditions (Kim, 2000). Discrete event simulation methodology is used for modeling of vertical lifting with transfer operation, and scatter search of metaheuristic methodology is used for analyzing the optimal transfer floor.

1.3 Research Process

Figure 1 represents the process of the research. Following process was established for the study on construction lift system with transfer operation.

First, analysis and review of previous studies on current lift operation system on construction sites were processed. From these analysis and review, problem of this research was identified, regarded to adaptation of lifting system with transfer operation.

Next process was to select appropriate methodologies for assessing the problem of this research. As previously mentioned, a simulation methodology was adopted for analyzing various conditions on construction sites. With the simulation model, research could be carried out with short period of time and minimum resources.

After the selection of methodology, establishing the simulation model of construction lift system with transfer operation were carried out. A single module which represents the lift's operation was first made, then the lift system with transfer operation was constructed with the combination of multiple modules. Optimization model for analyzing the optimum transfer floor then added to the simulation model.

Since there was few applicable actual cases where transfer operation were adopted, so the mock case was made for the research. With this mock model, multiple experiments with different top floors were executed, and made suggested optimal transfer floor on each buildings with different top floors.

Another analysis was done, which showed the pattern of the change of consumed vertical lifting time on different transfer floors, assuming only transfer floor is changed with same building. This analysis showed how the change of transfer floor could affect vertical lifting time of workers.

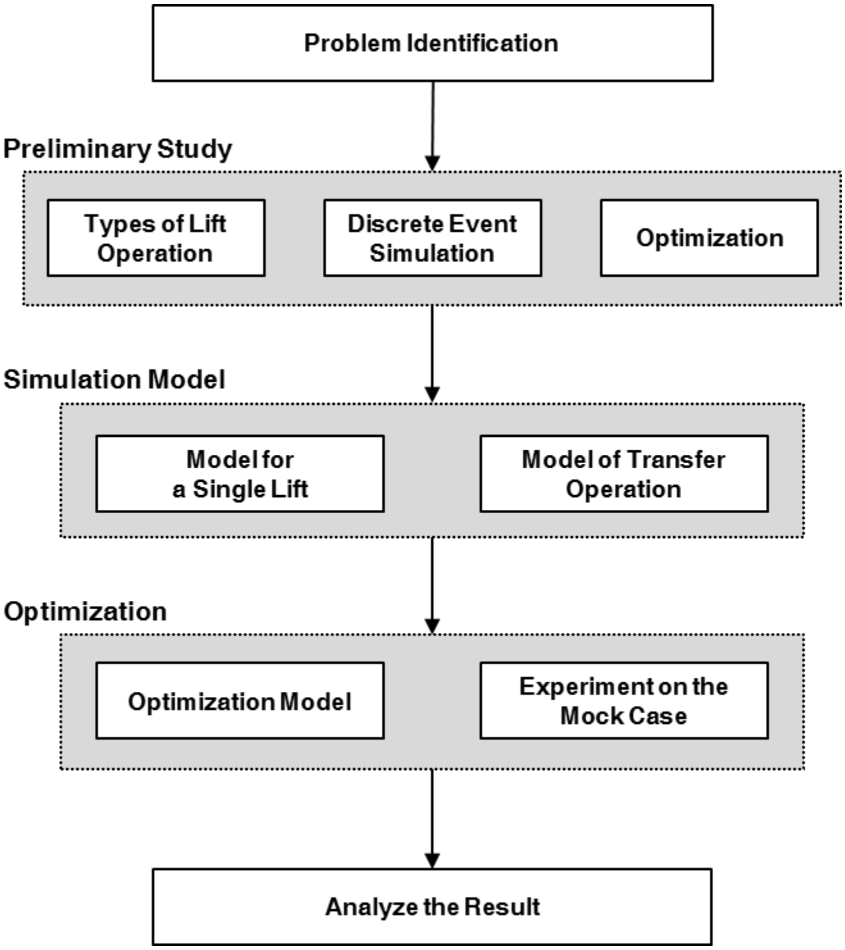


Fig. 1. Research Process

Chapter 2. Preliminary Study

2.1 Types and Characteristics of Lift Operation

Figure 1 is a concept diagram of 3 types of lift operation. In general, lift operation can be classified as 3 different types: All floor operation, zoning operation, and transfer operation. In all floor operation, each of lifts travel from the 1st floor to every floor. This is commonly used for most of construction projects. In zoning operation, each of lifts are designated certain vertical zones, and each of them travel from 1st floor to those floors in designated zone. In transfer floor operation, each of lifts are designated certain vertical zones, and they travel only within those floors in designated zones. So in order to get to the top floor, resources must be transferred at certain floor, and change the lift for upper zone.

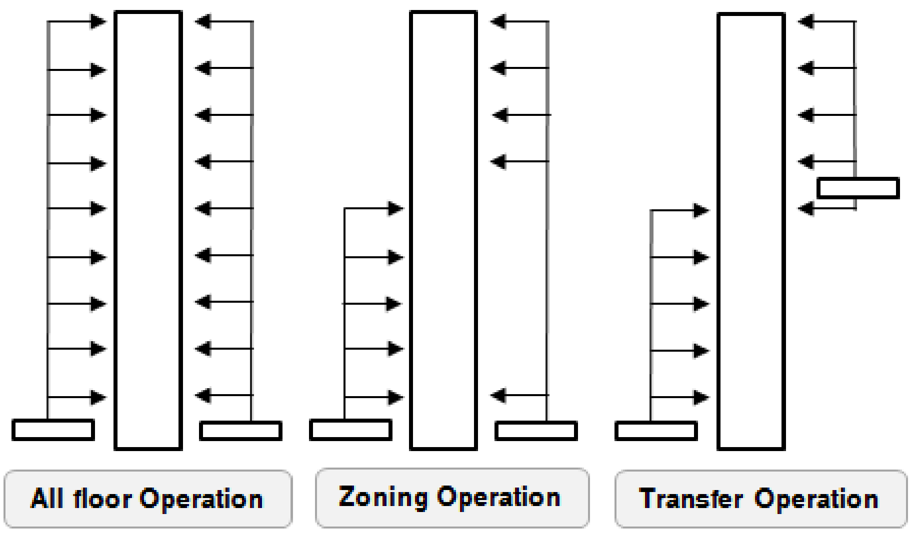


Fig. 2. Three Operation Types of Construction Lift System

2.2 Literature Review on Lift Operation

Table 1 is about previous studies on construction lifting. Previous studies on all floor operation were mainly about the appropriate number of lifts, types of lifts, and installation periods. Jung (2004) suggested the lifting planning process and the system of analyzing the quantities of materials using the causal relationship analysis. Kim (2008) presented the process of assessing the number of lifts using the analysis of costs and average peak time load. Shin (2010) established the system of evaluating the appropriateness of the selection of the number of lifts and type using the simulation methodology. Han (2012) suggested the conversion method for between the required amount of resources for vertical lifting and the lifting loads. And with the converted lifting loads, analysis method of lifting load and lifting cycle time were presented through the model of lifting load estimation. Cho (2013) used B&B algorithm (Branch and Bound Algorithm) for assessing the total consumed time with multiple lifts' operations, and suggested the optimal way of operation with the analysis.

In zoning operation, Park (2011) established the optimization model of lifting operations of workers with analysis of lifting process of peak time (morning) and optimal division of crews and vertical zones. However transfer operation has not been considered in previous studies in common.

Table 1. Researches on Construction Hoist Lifting

Authors	Points of Research	Contents
Cho. et al (2013)	Optimal Algorithm of the Multi-lifting operation Simulation	Suggestion of quantitative and systematic methods of lifting using an optimal algorithm with B&B algorithm
Kim. et al. (2008)	Assessing the no. of lifts	Peak time load, Assessing optimum no. of lifts considering workers on sites
Park. et al (2011)	Genetic Algorithm, Discrete Event Simulation	Suggesting optimization model for workers lifting operation through zoning vertical section at peak time
Shin, (2010)	Lift Selecting System	Suggestion of analyzing system for determining no. of lifts, types and propriety through simulation
Jung, et al (2004)	Causal Relationship Analysis	Suggestion of lift planning process and quantity calculation process through causal relationship analysis
Han, et al (2012)	Model of Assessing Lifting Load	Suggestion of lifting load assessment and process of lift planning process
Hwang (2009)	Survey and Expert Interview	Study on factors for researching decision making of lift planning for building construction

2.3 Discrete Event Simulation

Discrete event simulation is modeling the system observing the change of system's status on timely distinguishable points. This discrete event simulation methodology is used for dynamic and discrete model (Kim, 2002). In construction industry, many programs such as 'Cyclone' (Halpin, 1973), 'Stroboscope' (Martinez, 1996) have been utilized for studies using discrete event simulation.

Lifting of workers and lift operations, which are objects of this research, can be classified as an dynamic, discrete model since lifts' operations are vary based on the set of workers' target floors who are on board on each of lifts. So this model can efficiently analyzed by using the discrete event simulation methodology.

For constructing the model with discrete event simulation methodology, 'AnyLogic 7.0' application made by 'The AnyLogic Company' was used. 'AnyLogic 7.0' application provides tool for establishing the model with discrete event simulation. Many researches with discrete event simulation methodology carried out with 'AnyLogic 7.0' application (Chan, 2010; Banerjee, 2011).

2.4 Optimization with the Optimum Value Search

Simulation is a good tool for observing changes of status on system, but its role is limited to evaluate the values which are given. For finding the optimal variables, human needs to input certain values and judge the outcome, then followed by repetitive processes of changing the values.

In this research, scatter search technique is used as an optimization methodology. Scatter search can be used for problems like the optimization of combination, integer programming, and continuous variables (Ebrahim, 2009). Since transfer floor is an integer variable, scatter search methodology is selected for the optimization method.

For constructing the optimization model, ‘OptQuest’ application made by ‘OptTek System’ was used. ‘OptQuest’ application uses metaheuristic methodology combined with tabu search, neural networks, and scatter search. Multiple researches were carried out optimization using ‘OptQuest’ application (Laguna, 1997; Rogers, 2002; Jie, 2008).

2.5 Summary

As previously mentioned, lift systems with transfer operation have some unique characteristic, such as transfer floors, and different operation floors of the lifts. Also every type of lift operation itself has a variety of elements, which should be included to carry out the research.

For representing those complicated mechanism of lift operation, a discrete event simulation methodology is selected for establishing the model of lifts operation.

With discrete event simulation model, elements consisting of lift system with transfer operation can be represented and analyzed. Through establishing the connection between this model and the optimization model, it is possible to execute optimizations for the optimum transfer floor.

Chapter 3. Construction Vertical Lifting Simulation with Transfer Operation

For analyzing the vertical lifting with transfer operation, the model describing an operation of one lift should be established first. In the entire simulation model, this lift model is duplicated as much as the given number of lifts for lower and upper part of the system.

Lift simulation model is built using the discrete event simulation of AnyLogic 7.0, product of The AnyLogic Company Co. AnyLogic 7.0 application is capable of establishing discrete event simulation model, many researches using discrete event simulation methodology were carried out with the application (Chan, 2010; Banerjee, 2011).

3.1 Build a Model for Single Lift

A single lift model describe the operation of one lift. In the simulation model of lifting with transfer operation which many lifts are included in the model, the single lift model is copied as much as the required number of lifts. That is, if 10 lifts are used on the construction sites, there are 10 duplicated single lift models in entire simulation model.

Building the single lift model is processed by following procedures: Analysis of lift operation process, applying the algorithm of vertical lifting time assessment, and establishing the process of each module operation.

3.1.1 The Process of Lift Operation

Figure 2 represents the processes of lift operation and workers' movement. Lift operation process during the peak time (in the morning) should be considered separately from the workers' movement. For lifts, the process is same as they travel to every worker's target floors regardless of upper or lower zone. However for workers, process of workers who need transferring is different from those who do not need to transfer.

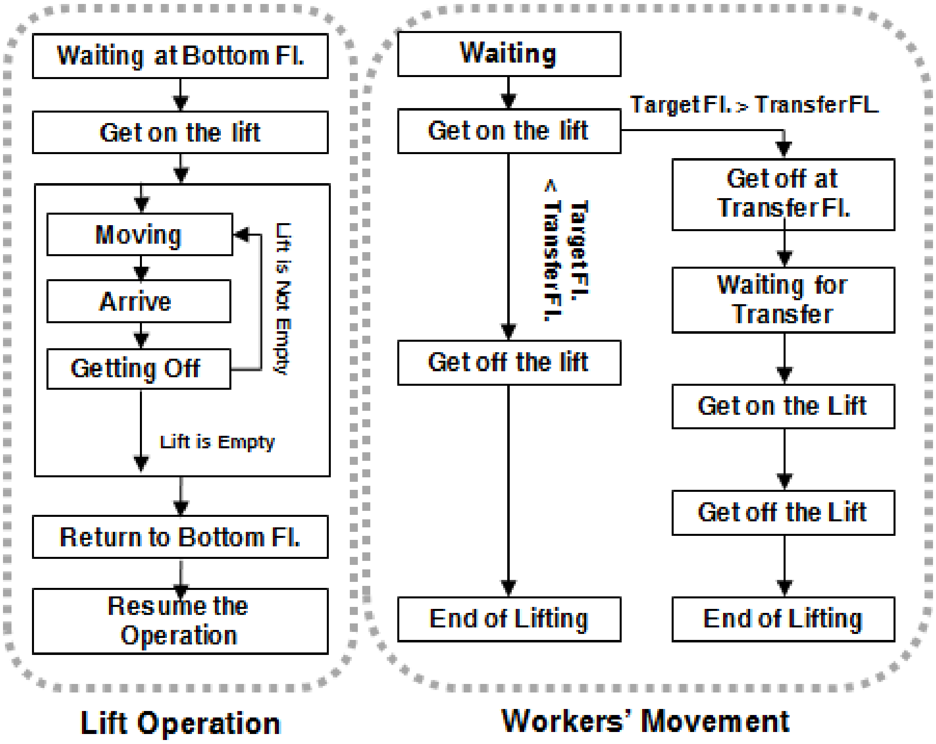


Fig. 3. Process of Lift Operation and Workers‘ Movement

3.1.2 Lift Operation Time Assessment Algorithm

In simulation model, each of lifts should calculate traveling time on every travels between floors. In this research, lifting operation time assessment algorithm in consideration of acceleration and deceleration suggested by Cho (2011) is adopted for calculation of lifts' traveling time.

Total traveling time of a lift (T_L) is defined as below.

$$T_L = T_m + L_t$$

T_m is pure traveling time of lift, L_t is the consumed time for worker to get on and off the lift. T_m can be calculated by the sum of traveling time in safe operation speed (T_p), acceleration time (S_1), and deceleration time (S_2).

$$T_m = T_p + S_1 + S_2$$

T_p is the sum of the followings: The time consumed for the remaining distance of acceleration after the required distance to finish the acceleration (T_{v1}), the time consumed for the remaining distance of deceleration after the required distance to finish the deceleration (T_{vn-1}), and the time consumed for traveling the rest of all (T_v).

$$T_p = T_v + T_{v1} + T_{vn-1}$$

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

(H = Standard floor height, h_1 = The distance to reach the safe operation speed, h_2 = The distance to reach stop, V = Safe operation speed of lift)

Time for workers to get on and off the lift (L_t) is sum of gate opening time (D_{vt}), closing time (D_{ct}), and get on/off time of workers (M_{lt}).

$$L_t = (D_{vt} + D_{ct} + M_{lt}) \times 2$$

Table 2. Variables of Lift Operation Time Assessment Algorithm (Cho, 2011)

Name	Represent
T_L	Total traveling time of a lift
T_m	Pure traveling time of a lift
L_t	The consumed time for worker to get on and off the lift
T_p	Traveling time in safe operation speed
S_1	Acceleration time
S_2	Deceleration time
T_{v1}	The time consumed for the remaining distance of acceleration after the required distance to finish the acceleration
T_{vn-1}	The time consumed for the remaining distance of deceleration after the required distance to finish the deceleration
T_v	The time consumed for traveling the rest of all
H	Standard floor height
h_1	The distance to reach the safe operation speed
h_2	The distance to reach stop
V	Safe operation speed of the lift
L_t	Time for workers to get on and off the lift
D_{vt}	Gate opening time
D_{ct}	Gate closing time
M_{lt}	Get on/off time of workers

3.1.3 Module Operation Process

In this research, discrete event simulation module of each lift car's lifting through the following process: 'Distinguish each entities' parameters', 'Set variables of each entities', 'Events which variables change'. Details are as below.

(1) Variables and parameters of each entities

In this simulation model, entities represent lifts and workers. Variables and parameters of each entities are shown on Table 3.

(2) Event of variable change

Events occur as worker entities in simulation model move, and each of events change the variables. Figure 3 is the conceptual diagram which represents the change of variables on each parts of simulation in the single lift simulation model. Details of events are as below.

a. Worker arrives at the front of the lift for getting on

- Record the worker′s time of arrival
- Calculate the number of workers waiting

b. Worker gets on the lift

- Record the number of workers get on
- Calculate the consumed time of getting on
- Calculate the waiting time of workers
- If there is no works waiting and finished get on the lift, execute the event ′c. Analyze workers′ target floors′, and terminate the event ′b. Workers gets on the lift′ and set idle state.
- If lift is full, execute the event ′c. Analyze workers′ target floors′, and terminate the event ′b. Workers gets on the lift′ and set idle state.

c. Analyze workers′ target floors

- Analyze workers′ target floors from the lowest floor and record

d. Lifting

- Record the traveling time of lift
- Calculate the traveling time to target floor and apply
- Calculate the number of workers getting off the targeted floor

e. Arrive at the target floor and get off

- Apply the time consumed for getting off the lift regard to the number of workers get off at the floor
- Deduct the number of workers on the lift as workers get off at the floor
- Record traveling time of each workers
- Change the current floor of the lift
- If the lift is empty, execute the event ′f. Return operation′, if not, execute the event ′d. Lifting′ again

f. Return operation

- Change the direction of traveling of the lift to downward
- Analyze the current floor and the bottom floor on operation zone, then calculate the traveling time of returning to the bottom floor, and apply
- If return operation is finished, execute the event ′b. Worker gets on the lift′ again

Table 3. Variables and Parameters of Entities

Entity	Parameter	Variable
Lift	• Normal operation speed of lift • Acceleration Time • Deceleration Time • Distance to reach operation speed • Distance to reach stop • Maximum capacity • Floor height of standard Floor • Door opening time • Door closing time • Bottom Floor of Operation Section • Top Floor of Operation Section	• Current Floor • Moving Direction • Target Floor • Moving Time • Number of workers in Lift • Time of Getting on • Time of Getting off • Number of Workers Getting off Each Floor • Time of Returning to Bottom Floor
Worker	• Target Floor	• Current Floor of Worker • Initial time of arrival • Waiting Time • Moving Time • Lift Waiting Order

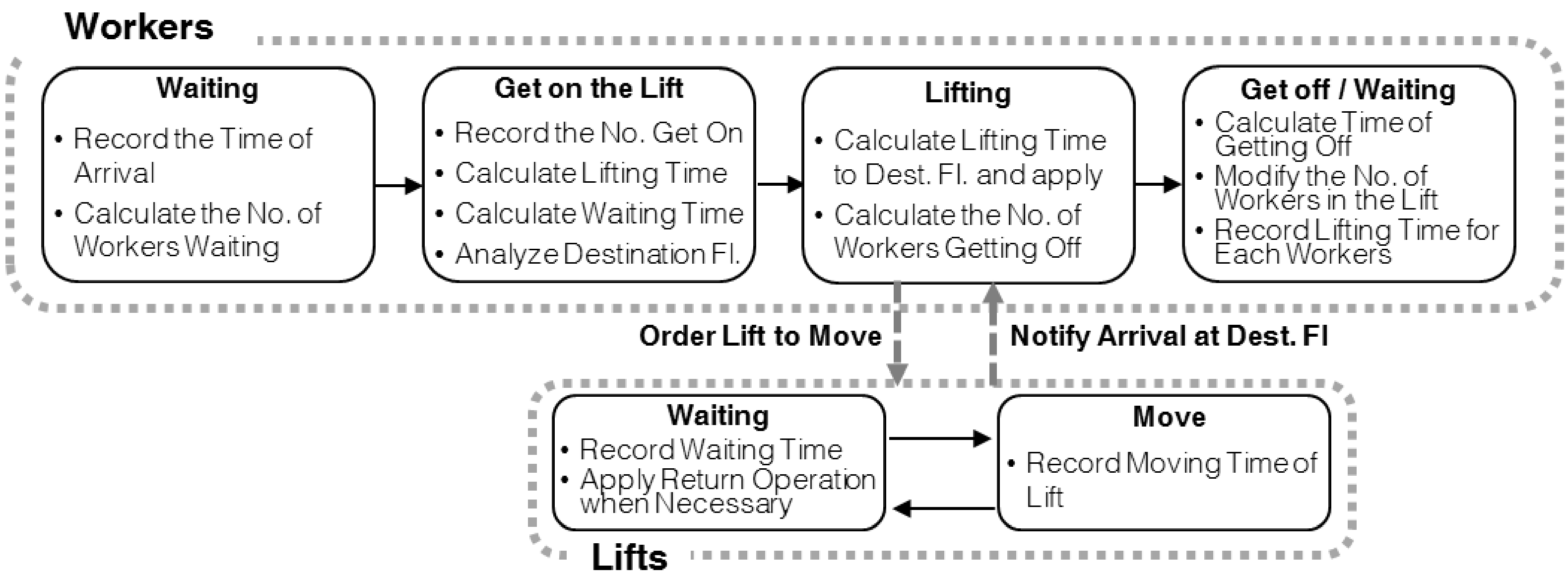


Fig. 4. Simulation Module of a Single Lift

3.2 Simulation Model of Lift with Transfer Operation

The simulation model of lifting with transfer operation is established with the single lift model which presented above. During the modeling process of actual worker's vertical lifting, following assumptions are made for the simulation model.

(1) All workers arrive at the construction site at the same time when daily schedule is started, and they are assumed to be waiting for the lifting.

(2) Workers select their lift randomly with uniform probabilities on each lifts

(3) The required number of workers on each floors are assumed to be same

(4) The time consumed getting on/off the lift assumed to be same on all workers

(5) The first lifting of each of lifts are executed when the lift is full. After the first operation, lifts carry workers waiting in the line even if the number is below the maximum capacity.

(6) Lift operation is set to be normal, any unexpected malfunction or mistake on stop point are excluded.

(7) Since it is the peak time (morning), the direction of workers vertical lifting assumed to be upward only.

(8) Elevators which are installed during the construction period are not included in the model.

(9) Same type of lift is applied for all lifts.

Figure 4 is the schematic diagram for simulation model of lifting with transfer operation. Events on each parts and details are as below.

(1) Generate workers entities / Designate destination floors

- Generate workers entities

- Evenly distribute designate destination floors for workers

(2) 1st lift selection

- Randomly select one of lifts on lower zone

(3) 1st lift module

- Execute lifting simulation within each lifts′ module

(4) Analyze the final destination

- If worker needs to transfer, send the worker to the upper zone lift for transferring
- If worker reached to the destination, calculate and record the total traveling time

(5) 2nd lift selection

- Randomly select one of lifts on upper zone

(6) 2nd lift module

- Execute lifting simulation within each lifts′ module

(7) End of simulation

- Calculate and record the total traveling time

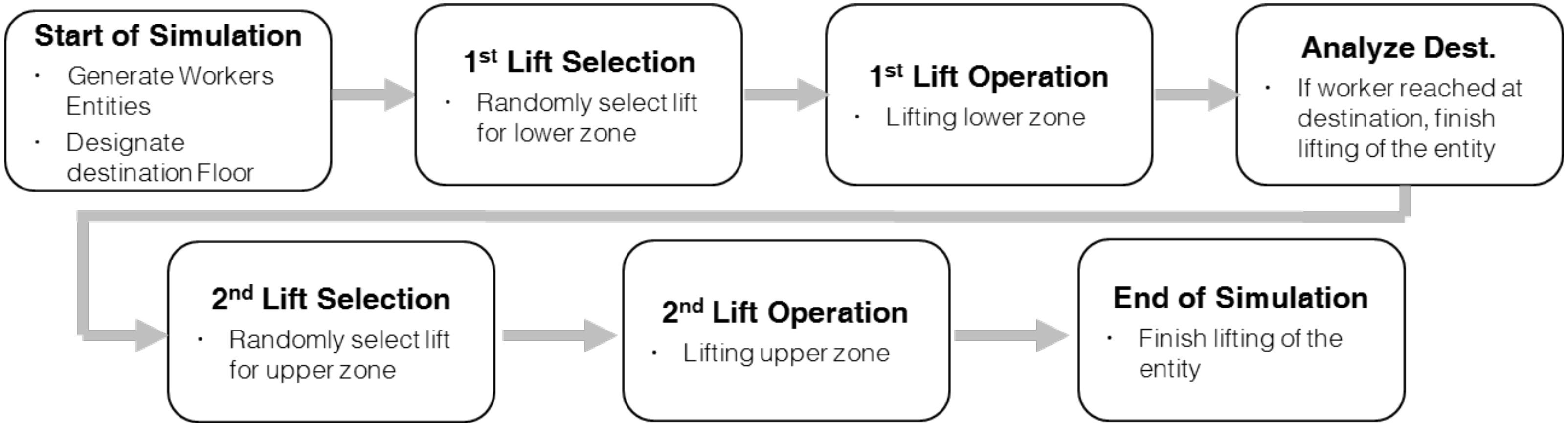


Fig. 5. Lifting Simulation Model with Transfer Operation

3.3 Summary

For dealing with multiple lifts scenario, simulation module of one lift is established first. For the module, lift operation time assessment algorithm (Cho, 2011) is adopted, and operation process of lift is established.

Lift modules are duplicated as many as the number of lifts which are to be analyzed. This gives a flexibility on the analysis, which can meet different specifications of construction sites.

For representing the transfer operation, the process of operation at the transfer floor is established. With the process, the module for transfer operation at the transfer floor is constructed and included in the overall simulation model.

Chapter 4. Optimization and Experiment on the Mock Case

In this research, the model of optimization of transfer floor is established with the previously built simulation model. Through this optimization model, experiments on optimization of transfer floor for the mock case are carried out. Also analysis of lifting time variation with changes of transfer floor is done by using the mock case as well.

4.1 Optimization Model

The purpose of optimization in this study is set as to minimize the average vertical lifting time of workers. Decrease of workers vertical lifting time leads to increase of possible working hours on worksites. Also this can bring the save of costs and shortening the construction period by increasing the workers' efficiency. So in this model, optimal transfer floor is defined as the location where the average lifting time or total lifting time of workers are minimum.

Worker's traveling time (T_{wt}), total traveling time of all workers (T_{Hwt}), and average traveling time (T_{Awt}) are defined as below.

$$T_{wt} = T_{t1} + L_{t1} + T_{L1} + L_{t2} + T_{w2} + L_{t3} + T_{l2} + L_{t4}$$

$$T_{Hwt} = \sum_{i=1}^{n} T_{wt} \qquad T_{Awt} = \frac{T_{Hwt}}{n}$$

T_{w1} : Waiting time at the 1st floor before getting on the lift
L_{t1} : Time consumed for getting on the lower zone lift
T_{L1} : Traveling time of lower lift
L_{t2} : Time consumed for getting off on lower/transfer floor
T_{w2} : Waiting time at the transfer floor before getting on the lift
L_{t3} : Time consumed for getting on at the transfer floor
T_{l2} : Traveling time of upper lift
L_{t4} : Time consumed for getting off at upper floor
n : Number of total workers

In this research, optimization analysis is done using OptQuest application capable of using metaheuristic algorithm product of OptTek System Co. OptQuest application operates through the metaheuristic algorithm which is the combination of tabu search, neural networks, and scatter search (Rogers, 2002). Many studies on search of optimal value were carried out using OptQuest application, and they suggested OptQuest application for finding the optimal value in the manner of reliability and efficiency (Laguna, 1997; Rogers, 2002; Jie, 2008). OptQuest application can be linked to AnyLogic 7.0 application, so the simulation model on AnyLogic 7.0 is interconnected to the optimization model on OptQuest application, and the optimization analysis can be executed.

Figure 5 represent the process of optimization analysis, and details of each processes are as below.

(1) Input the value of top floor

(2) Set the transfer floor variable which is the target of optimization

- Set the possible range of transfer floor from the lowest possible floor to the highest possible floor. In this research, the lowest floor is set to be the 1st floor, and the highest is set to be the top floor
- Set the unit of the optimal value. Since the number of floors are natural

number, so the unit is set as 1

- For the efficiency of the optimization, input the suggested optimal value. If the model has a suggestion value, it searches values near the suggested value first, so the optimization can be faster. In this research, a half of the top floor is input as the suggested value (e.g. If the top floor is 100 floor, then suggest value is 50)

(3) Setup the object of optimization

- Set ʻMinimize the total vertical lifting time of workersʹ as the object of this optimization analysis

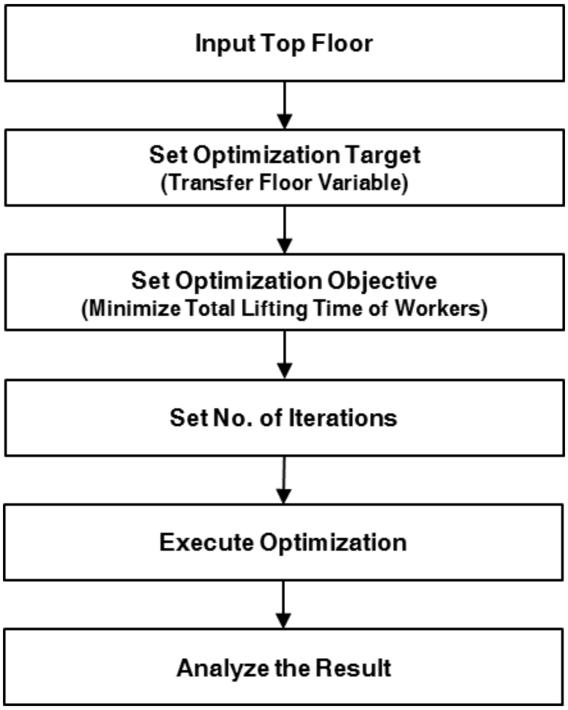
(4) Set the number of iteration

- In case of massive computation works for the search of optimal value, the maximum number of iteration is set for preventing infinite loops of computations. In this research, 1,000 iterations are executed for each optimization

(5) Execute searches of the optimal value

(6) Check the processed optimal value

Fig. 6. Process of Optimization Analysis



4.2 Experiment on Optimizing Transfer Floor with the Mock Case

In this research, the mock case project is made for the experiment of optimization of the simulation model. Table 3 represents details of experimental case project. Table 4 represents average acceleration and deceleration of various lift types (Cho, 2011).

Table 5 is the results of optimal transfer floors for each 10^{th} floors through the optimal value search of the optimization analysis. The difference of the average lifting time of workers for transfer floor of the half of top floor and the optimized floor is from 1 minute to 6 minutes. In the perspective of whole workers, total reduced lifting time is from 26 hours to 100 hours. This optimization is for a peak time of one day situation, the effect of reduced lifting time using the optimized transfer floor is significant throughout the whole construction project, even if only finishing work period after the framework is considered.

Table 4. Details of the Mock Case Project

Parameter	Value
Top Floor	From 100 to 200, Each 10 floors
Lift Type	Mid Speed (Details are in Table 4)
No. of Workers	1,000
No. of Lifts	3 in Lower Fl., 2 in Upper Fl.
Time of Workers Getting On/Off	0.5sec/person
Time of Opening Door	5 Sec
Time of Closing Door	1 Sec
Standard Floor Height	4m
Max. Capacity of Lift	20 People

Table 5. Average Acceleration and Deceleration of
Various Lift Types (Cho, C. 2011)

Type	Normal Operation Speed (m/sec)	Accelera-tion Time (Sec)	Decelera-tion Time (Sec)	Accele-ration (m/sec2)	Distance to Reach Normal Speed (m)	Deceleration (m/sec2)	Distance to Reach Stop (m)
High	1.67	2.80	2.90	0.60	2.33	0.57	2.42
Mid	1.00	5.00	2.90	0.20	2.50	0.34	1.45
Low	0.63	1.00	1.00	0.63	0.32	0.63	0.32

Table 6. Optimization Result of Transfer Floors

Top Floor	Optimized Transfer Fl.	Average Lifting Time (Hour)	1/2 Fl.	Aver. Lifting Time when 1/2 Fl. (Hour)	Difference of Aver. Time to Optimized Transfer Fl.(Hour)	Total Shortend Time by Optimized Transfer Fl. (Hour)
100	**45**	1.268	50	1.295	0.026	26.620
110	**47**	1.358	55	1.409	0.051	51.415
120	**54**	1.446	60	1.514	0.067	67.650
130	**61**	1.544	65	1.589	0.045	45.357
140	**64**	1.608	70	1.656	0.048	48.292
150	**67**	1.668	75	1.712	0.044	43.650
160	**71**	1.756	80	1.811	0.055	55.054
170	**77**	1.851	85	1.921	0.100	100.020
180	**78**	1.871	90	1.973	0.101	101.604
190	**80**	1.964	95	2.042	0.077	77.821
200	**90**	2.060	100	2.121	0.061	61.102

4.3 Analysis of Lifting Time Variation with Changes of Transfer Floor

Previously the optimization of transfer floors for different building heights is carried out. Also the analysis of the difference of average lifting time between the half floor of the top floor and the optimized transfer floor has been made. In addition to these, another analysis has been made, which is about the variation of average lifting time when transfer floor is changed by 1 floor. Experiment case project is same as used in Chapter 4.2, and top floors for the analysis is 100, 125, 150, 175, 200 floors. Each heights have 50 floors range of transfer floors and simulated by 1 floor.

Simulation results are represented to Figure 6 to Figure 10. As shown on the graphs, average lifting time is increased for every 1 floor increased or decreased from the optimal transfer floor. The rates are vary on different heights of buildings, but it is relatively regular within the same height.

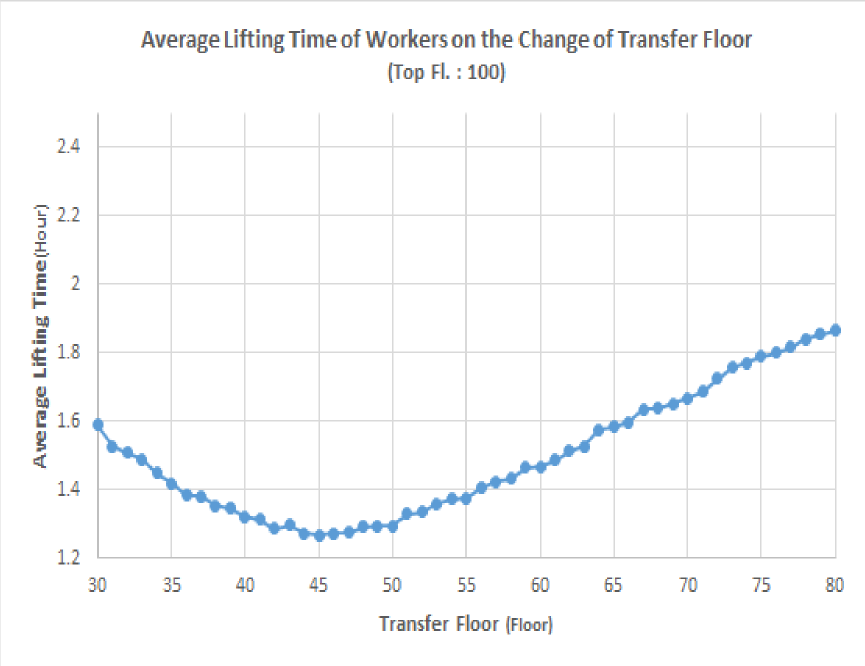


Fig. 7. Change of Average Lifting Time for Transfer Floor Variation

(Top Floor : 100)

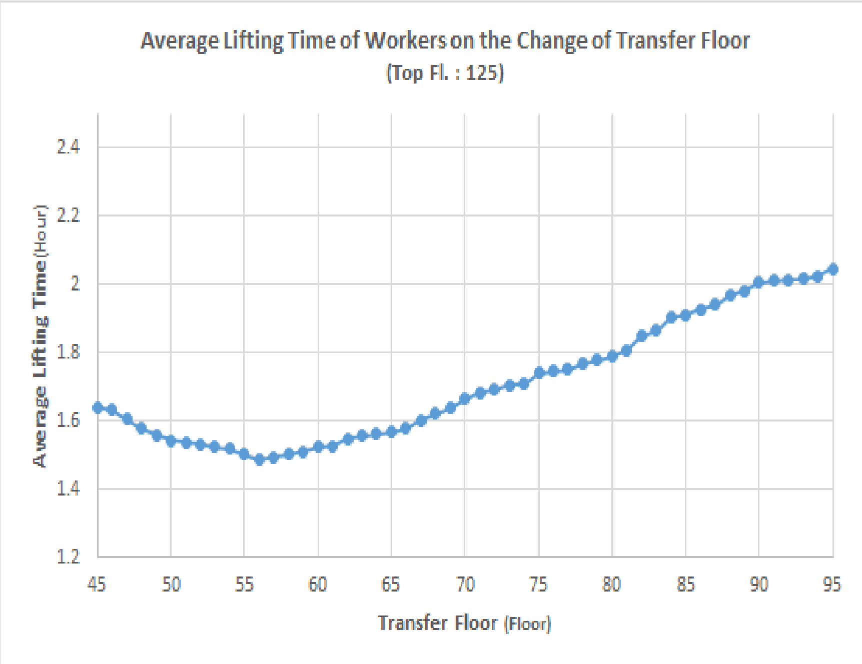


Fig. 8. Change of Average Lifting Time for Transfer Floor Variation

(Top Floor : 125)

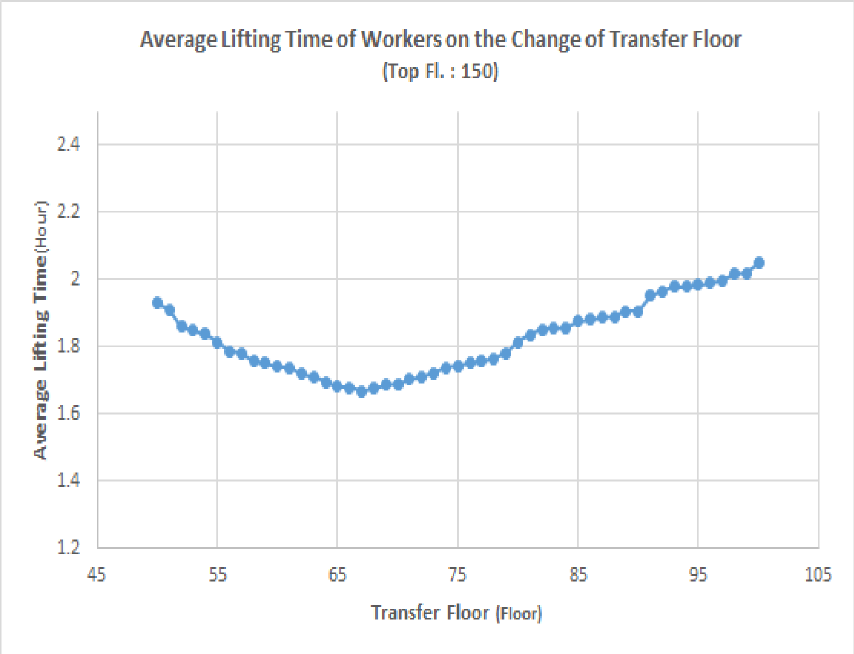


Fig. 9. Change of Average Lifting Time for Transfer Floor Variation

(Top Floor : 150)

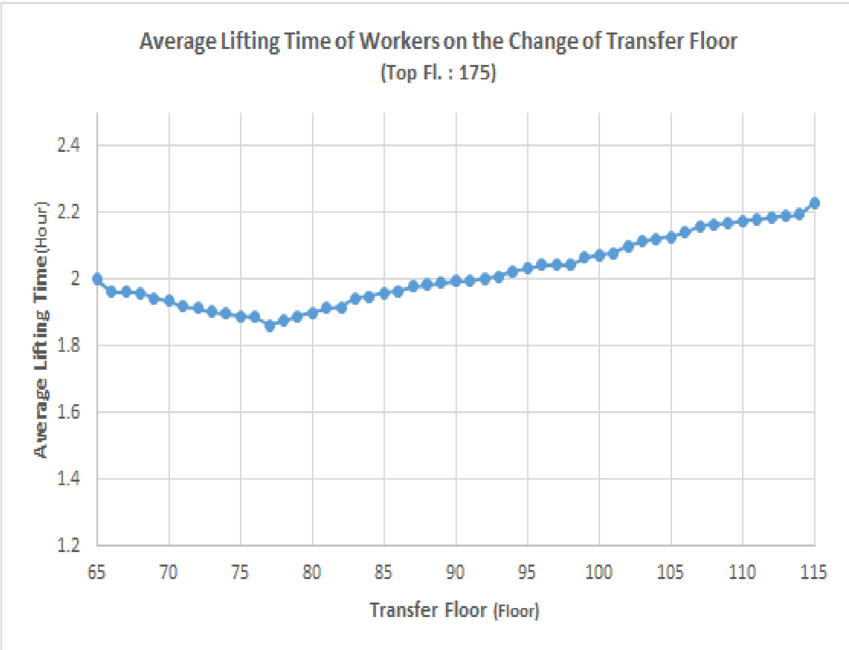


Fig. 10. Change of Average Lifting Time for Transfer Floor Variation

(Top Floor : 175)

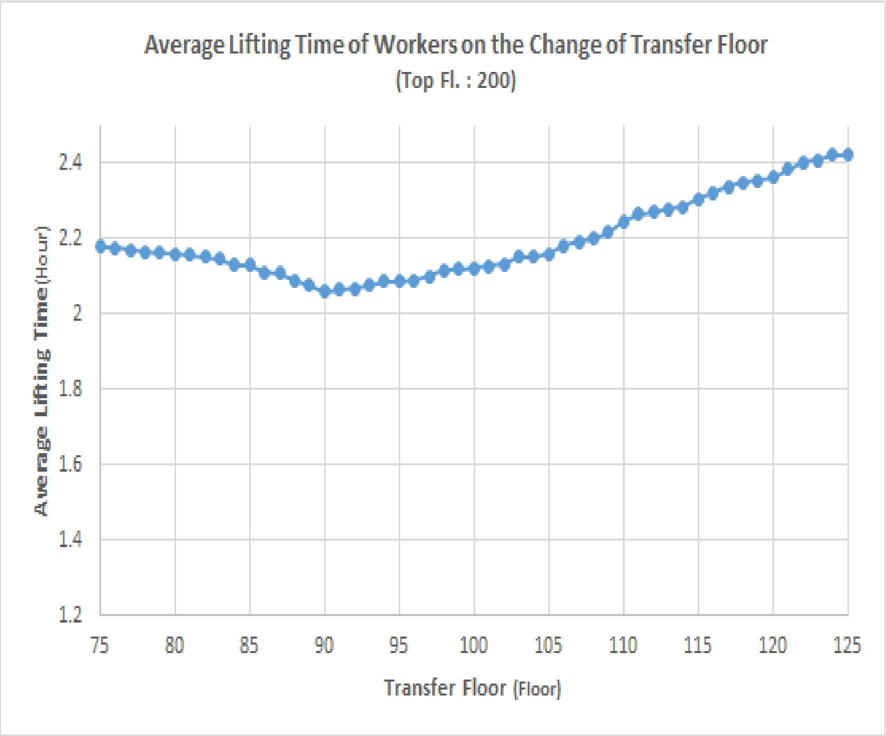


Fig. 11. Change of Average Lifting Time for Transfer Floor Variation
(Top Floor : 200)

4.4 Summary

With the simulation model of transfer operation, the optimization model is constructed using scatter search algorithm. For the optimization, the process of optimization process is established. By using OptQuest application, optimization model is connected to the simulation model which is built on AnyLogic 7.0 application.

For the analysis, the mock case is used, details are shown in Table 3. Optimization model showed the optimized transfer floor on each top floors, and showed the significant difference of average lifting time with the case of using non-optimized transfer floor.

Another analysis also showed the pattern of the change of average lifting time on transfer floor variation. From the optimal transfer floor, average lifting time is increased as it decreased or increased.

Chapter 5. Conclusion

5.1 Results and Contribution

As many buildings become to be high-rise around the world, the importance of the efficiency of vertical lifting on building construction is increasing. High vertical lifting efficiency can make workers use more time on the operation on sites, and this can result to save of cost and shorten the construction project period. Especially those buildings’ which are over 100 floors, lifting with transfer operation is essential for securing the reliability of lift operation and minimizing the risk of delay on construction period.

For the simulation model of lifting with transfer operation and the optimization model for optimal transfer floor, followings were carried out in this research.

(1) Established the simulation model of vertical lifting with transfer operation using the discrete event simulation methodology

(2) Built the analysis tool of optimizing transfer floors with optimal value search program using metaheuristic algorithm

(3) Analyzed the optimization of transfer floor with the experimental case project, and showed the difference of average lifting time between a half floor of top floor and the optimized floor

(4) Analyzed the variation of worker′s average lifting time on the change of transfer floor with fixed top floor

Through this research, the way of considerably reducing vertical lifting time through setting the optimized transfer floor is suggested. If the simulation model of lifting with transfer operation and the optimization model of analyzing the optimal transfer floor are used, workers can reach to their destination floor more quickly during the peak time by setting the optimal transfer floor on each construction site. This can increase workers' operational hours per day, also result to save of construction cost with reduced overall labor costs, and decrease the construction period. Even if optimal transfer floor cannot be used by other constraints, the simulation model can analyze the selected transfer floor and provide background data for decision making of overall construction project.

5.2. Limitation and Future Study

In the process of applying the result of this research, following limitations should be considered.

(1) The result of this research is for a peak time of a day. Construction process is not considered.

(2) Among the vertically-lifting-needed resources, lifting loads of workers are included only in the research.

(3) The number of transfer floor is set to be one.

(4) Elevators that are installed during the construction phase is not considered.

(5) Top floor is assumed to be same during the optimization.

For enhancing the adaptability of this research for actual construction site, follow-up studies are necessary as below.

(1) Applying different demands of manpower on each floor based on actual construction process

(2) Including finishing materials in the simulation model, which is one of main vertical lifting load

(3) Assessment of the optimal number of lifts and types through the simulation and optimization in consideration of lifting load of workers and materials linked to actual construction process

(4) Optimization of the number of transfer floor

(5) Include the use of installed elevators during the construction period

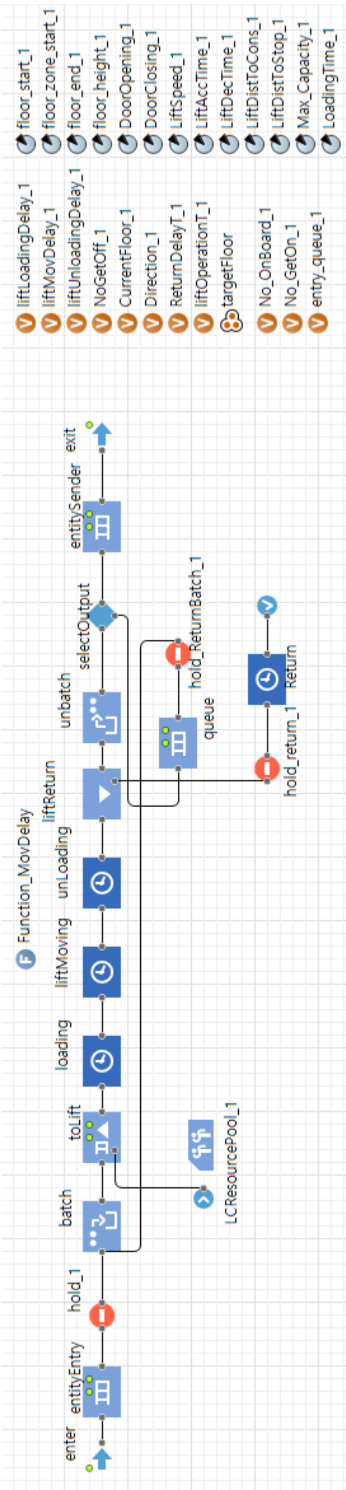
(6) The change of top floor with the progress of frame work during the construction period

5.3. Conclusion

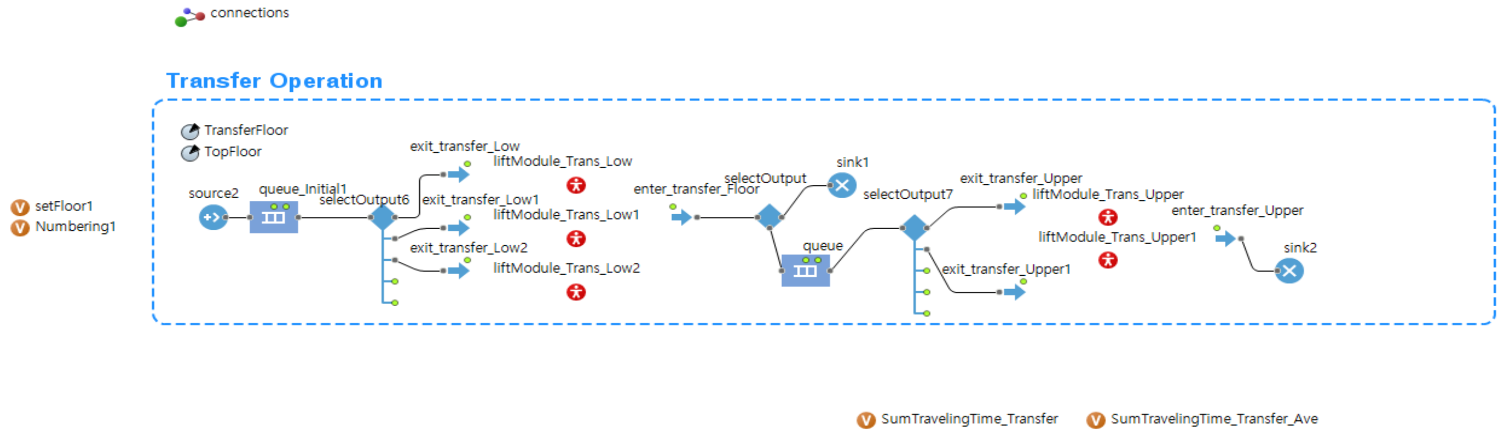
With worldwide rapid urbanization phenomenon, the number of super high-rise construction projects will continue to increase in foreseeable future. However, due to the limit of maximum travel distance of lift car, transfer operation is required for super high-rise building construction projects with more than 100 floors high.

In this research, the importance of the location of transfer floor was analyzed, and approach to assess the optimal transfer floor was made. Since lifting should be planned at the early stage of construction projects, using simulation methodology can be an appropriate option. Properly planned vertical lifting may result in save of cost and time especially on super high-rise building construction project. Combined with the results of further studies which previously mentioned, optimal lifting plan with transfer operation can be made through the simulation model.

Appendix 1. Lift Simulation Model



A Single Lift Simulation Model in AnyLogic 7.0



The Lift Simulation Model with Transfer Operation in AnyLogic 7.0

Java Class: Resource

Name	Value
General	

Text	/**
	 * Resource
	 */
	public class Resource extends Agent implements Serializable {
	
	public int ID;
	
	public int Type;
	
	public double ArrivalT;
	
	public int Destination;
	
	public double WaitingT;
	
	public double TravelingT;
	
	public String State;
	
	public double TotalT;
	
	public double TempT;
	
	public int TempDest;
	
	public int LiftSelection;
	
	/**
	 * Default constructor
	 */
	public Resource() {
	}
	
	/**
	 * Constructor initializing the fields
	 */
	public Resource(int ID, int Type, double ArrivalT, int Destination, double WaitingT, double TravelingT, String State, double TotalT, double TempT, int TempDest, int LiftSelection) {
	this.ID = ID;
	this.Type = Type;
	this.ArrivalT = ArrivalT;
	this.Destination = Destination;
	
	this.WaitingT = WaitingT;
	this.TravelingT = TravelingT;
	this.State = State;
	this.TotalT = TotalT;
	this.TempT = TempT;
	this.TempDest = TempDest;
	this.LiftSelection = LiftSelection;
	}
	
	@Override

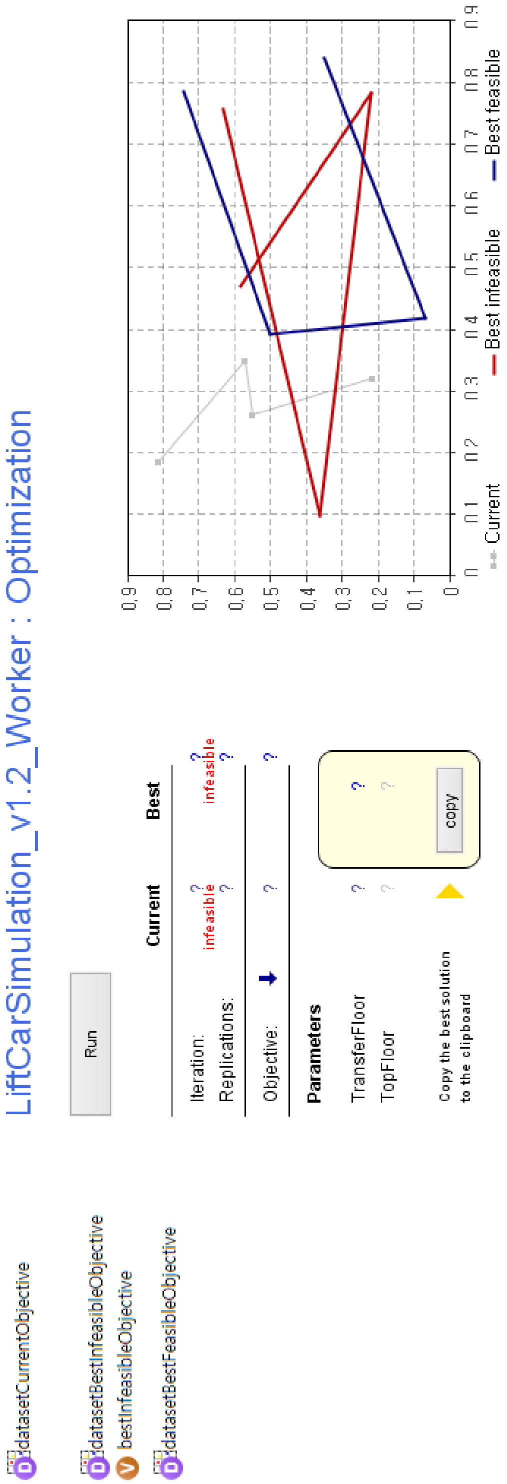
```
	public String toString() {
		return
			"ID = " + ID +" " +
			"Type = " + Type +" " +
			"ArrivalT = " + ArrivalT +" " +
			"Destination = " + Destination +" " +
			"WaitingT = " + WaitingT +" " +
			"TravelingT = " + TravelingT +" " +
			"State = " + State +" " +
			"TotalT = " + TotalT +" " +
			"TempT = " + TempT +" " +
			"TempDest = " + TempDest +" " +
			"LiftSelection" + LiftSelection +" ";
	}

	/**
	 * This number is here for model snapshot storing purpose<br>
	 * It needs to be changed when this class gets changed
	 */
	private static final long serialVersionUID = 1L;

}
```

Java Class: Lift

Name	Value
General	

Text	/**
	 * Lift
	 */
	public class Lift extends Agent implements Serializable {
	
	public int ID;
	
	public int Direction;
	
	public int CurrentFL;
	
	public double TempT;
	
	/**
	 * Default constructor
	 */
	public Lift() {
	}
	
	/**
	 * Constructor initializing the fields
	 */
	public Lift(int ID, int Direction, int CurrentFL, double TempT) {
	this.ID = ID;
	this.Direction = Direction;
	this.CurrentFL = CurrentFL;
	this.TempT = TempT;
	}
	
	@Override
	public String toString() {
	return
	"ID = " + ID +" " +
	
	"Direction = " + Direction +" " +
	"CurrentFL = " + CurrentFL +" " +
	"TempT = " + TempT +" ";
	}
	
	private static final long serialVersionUID = 1L;
	
	}

Appendix 2. Optimization Model



Optimization Model with OptQuest

Optimization Experiment: Optimization

Name	Value
General	
Maximum Available Memory	2048
Automatic Stop	false
Iteration Count	1000
Stop After Iteration Count	true
Objective Function Code	root.SumTravelingTime_Transfer
Objective	MINIMIZE
Agent Type	Main
Model time	
Use Calendar	true
Stop Option	Stop at specified time
Initial Time	0.0
Final Time	5.26176E7
Initial Date	Tue Apr 01 00:00:00 GMT 2014
Randomness	
Random Number Generation Type	randomSeed
Selection Mode For Simultaneous Events	LIFO
Replications	
Use Replications	true
Fixed Replications Number	false
Minimum Replications	3
Maximum Replications	10
Confidence Level	LEVEL_80
Confidence Error Percent	0.5
Window	
Experiment Progress	true
Title	LiftCarSimulation_v1_Worker : Optimization
Width	1000.0
Height	600.0
Enable Panning	true
Enable Zoom	true

Name	Value
Maximized	false
Close Confirmation	false
Java actions	

Before Each Experiment Run	datasetCurrentObjective.reset();
	datasetBestInfeasibleObjective.reset();
	datasetBestFeasibleObjective.reset();

After Iteration Code	if (isBestSolutionFeasible()) {
	datasetBestFeasibleObjective.update();
	}
	if (!isCurrentSolutionFeasible()) {
	bestInfeasibleObjective = min(bestInfeasibleObjective, getCurrentObjectiveValue());
	}
	if (bestInfeasibleObjective != Double.POSITIVE_INFINITY) {
	datasetBestInfeasibleObjective.update();

Advanced	
Allow Parallel Evaluations	true
Load Root From Snapshot	false

Parameter	Type	Value		
		Min	Max	Step
TransferFloor	INTEGER	40	180	1
TopFloor	FIXED			

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국 문 초 록

초고층 건축공사에서의 환승운영방식 리프트 시뮬레이션 모델 및 최적화 연구

최근 세계 경제가 금융위기로부터 회복되기 시작하면서 전 세계적으로 초고층 건축공사 프로젝트가 증가하는 추세에 있다. 수직 리프트 양중은 리프트 양중 장비 대수의 제약으로 인해 초고층 건축공사 프로젝트에 있어서 전체 프로젝트의 생산성 측면에서 매우 중요한 요소이다. 특히 건물 높이가 400m 이상 되는 초고층 건축공사에서는, 리프트의 최대 운행높이로 인해 환승운영방식의 리프트 양중이 필수적이다. 환승운영방식 리프트 양중에서의 환승층 지정은 자원들의 양중 시간 단축에 많은 영향을 미친다.

본 연구에서는 AnyLogic 프로그램을 통한 이산사건 시뮬레이션 방법론을 통해 단일 리프트에 대한 시뮬레이션 모듈 및 이를 이용한 전체 환승운영방식 리프트 운영 시스템의 모델을 구축하였다. 이에 기반하여 메타 휴리스틱 방식의 최적해 탐색을 사용하는 환승층 최적화 모델을 OptQuest 최적화 프로그램 상에서 제작하였다. 이를 이용하여 오전 출근시간대의 작업원 양중 시 환승층 최적화를 위한 방법을 제안하였다.

중간층을 환승층으로 지정했을 때와 비교한 결과, 최적 환승층을

지정했을 때 작업자들의 전체 양중시간이 상당히 단축되는 것으로 분석되었다. 아울러 환승층 변화에 따른 작업원 양중시간 변화 패턴도 분석 및 제시하였다.

본 연구에서 제안하는 도구를 사용 시 초고층 건축공사 프로젝트에서 작업원들의 가용 작업시간 증가를 통한 비용 절감 및 프로젝트 공기 단축이 가능할 것으로 예상된다.

주요어: 건설 리프트, 환승운영방식, 효율성, 초고층 건축공사, 환승층, 최적화, 시뮬레이션

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