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Mathematical model to optimally solve the lift planning problem in high-rise construction projects

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ABSTRACT

The availability of resources such as workforce and materials at each level of a high-rise construction project just before the commencement of building tasks is a crucial issue that might have direct impacts on project progress. To avoid delays caused by lack of human resources and construction materials, a construction management team always tries to find a better way to facilitate supply chain process specifically for construction projects facing a significant number of simultaneous and repetitive tasks. The other challenge in a high-rise construction project is vertical transportation that requires special machinery e.g. cranes or lifts, and also, maximizing their utilities. In this paper, it is tried to automate vertical transportation planning process in high-rise construction projects by introducing a platform that handles the entire lifting process. This platform considers (i) tasks attributes (e.g. required resources, location and commencement time) from the project schedule, (ii) lifting system specifications (e.g. travel speed, weight, and volume capacity) and (iii) project geometrics (e.g. current height of the project). In details, the introduced platform provides an optimized daily delivery plan by developing a Mixed-Integer Programming (MIP) model that covers workforce and construction materials. In this paper, the proposed platform is also tested using field data obtained from a 34-story construction project in Mashhad, Iran. The model could find a solution with 0% optimality gap in approximately 1 h, which is an acceptable amount of computational cost for the problem. The results show how the introduced platform can assist the construction management team to efficiently handle the supply process within stories while avoiding delays caused by a lack of resources required for each task.

1. Introduction

The ever-increasing demand for commercial, accommodation and housing spaces in limited available metropolitan areas has forced business owners to consider high-rise buildings as a practical solution [1]. The tight schedule of a high-rise building construction project necessitates the simultaneous execution of construction activities. This will result in a higher vertical transportation demand compared to other types of building projects [2]. In a high-rise building construction project, there is a significant number of construction activities executed in different areas and levels of the building. Most of these activities are special operations, which means that these tasks require special materials and equipment in order to be conducted. These activities and workers who perform them will be idle if the required resources are not delivered on time to the tasks' locations [3,4]. A project completion time relies on the accomplishment of project tasks, which again depend on the timely supply of materials and workforce. In the literature, there are a considerable number of studies devoted on just-in-time materials and workforce delivery (such as [5–9]). However, there are only a few studies related to optimal delivery solutions [10–15]. Not considering this subject in a construction project can result in severe delays due to a shortage of the necessary resources in sites which can pose significant delays to the project [16]. In this paper, after establishing a core of information between involved parties, a mathematical model is introduced to mitigate delays caused by unavailability of materials and workforce at task location.

Tower cranes are important tools for horizontal material transportation on every construction site. However, when it comes to vertical transportation in high-rise construction sites, their vertical reach is limited, and the lifting device will be the main practical option. The vertical range of a lifting system can be upgraded by extending the height of the mast, along which the lift car moves.

As it was discussed above, one of the necessary tools for vertical transportation is lifting equipment. Now there is a question which is not fully answered as to how managers should handle vertical transportation of workforce and materials in a high-rise building project so as to

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minimize costs while meeting all construction tasks' requirements?

In practice, most of the construction projects do not have a lifting plan, and expert workers handle lifting. It is evident that this approach will impose delays and extra costs especially when a lift becomes the bottleneck of supply chain process for a project [2,4,17]. This problem can be easily avoided by using a precise lifting plan, while having an imprecise lifting plan in the early stages of a construction project can pose other problems such as leaving the elevator lift car idle or failing to deliver the resource materials on time. A just-in-time concept is often adopted in the construction of high-rise buildings to increase the efficiency and better utilization of the limited spaces. Also, the number of lift stops and traveling distance in each roundtrip can quickly increase if inefficient lifting management is implemented, which will lead to a rise in lift cost [2].

Moreover, the vertical transportation demand in a high-rise building fluctuates during a working day. This demand usually peaks in certain periods (e.g., at the start, and at the end of a working day). The morning peak hour is of substantial importance in a high-rise building construction due to demand for workforce travel [16]. In a construction project schedule, those activities that are on the critical path must be prioritized since any delay in these activities will directly affect the overall project schedule. To prevent this risk, the resources must be transported to the right place at the right time [18], especially when dealing with activities that can be only supplied with lifts.

In the following sections, we first review a number of related literature and discuss the lifting operations and related factors. Then briefly, the graph theory preliminaries are presented which is the main theoretical basis for the lift planning mathematical model. The modeling process and the formulation are then presented and discussed in details. Finally, the developed model is implemented and tested by using a real-world case, and finally, results and conclusions are provided.

2. Literature review

In the previous section, the significance of studying the vertical transportation equipment in construction projects was addressed. In this section, previous research on this subject is briefly investigated, and a comparison has been made between this research and previous studies.

Few studies have been conducted on developing mathematical models to assist construction managers and lift operators. These studies have attempted to plan an efficient lifting schedule that can generally be divided into three categories: (i) lifting intelligent control systems, (ii) simulation techniques and (iii) lifting time calculation algorithms.

(i) *Lifting intelligent monitoring and control systems*;

Sacks, Navon [19] introduced the concept of an automated monitoring system for the lifting equipment. Their system is based on Building Information Model (BIM), which employs a black box monitor in the lifting equipment. This system gathers and delivers real-time data with acceptable accuracy. Cho, Kwon [20] proposed a smart robotic lift concept, which can perform lift loading/unloading operations automatically and therefore, is suitable for being used at night using a wireless communication system. Lifting resources in a non-critical time of the day is the main advantage of this smart system. In a similar study Cho, Kwon [21] introduced a sensorized vertical material delivery system including a hoist-mountable intelligent toolkit, which aims to automate the vertical material delivery by sensing the material information and automatically routing them to the right place. This system does not decide on the delivery plan but helps alleviate the delivery process by automatically routing materials to the right place. The gathered information from the sensors can also be used for monitoring the overall status.

(ii) *Simulation techniques*

Few studies have been devoted on hiring simulation techniques in lifting operations process in construction projects. In this field, mainly the lifting process is being analyzed based on predefined scenarios, and it is tried to provide insights into the lifting process. Cho, Kim [22] presented a simulation-based method, which takes into account the experts` judgment. Shin, Cho [1] applied a discrete-event simulation model and a genetic algorithm to solve the lifting planning problem. The results indicate an improvement in the optimality of the solution, comparing to the solution proposed by an expert planner. Park, Ha [16] developed a simulation model by utilizing lift zoning configuration, considering dynamic lifting demands over the time [23]. In this paper, floors are divided into clusters of floors based on the total demands of floors during a specific time period (e.g. 30 days). This technique was proven effective in achieving an optimal and time-saving lifting plan. It is worth to be noted that lift zoning concept mainly does not deal with daily lifting plan and only focuses on floor clustering. Jung, Moon [2] applied the discrete event simulation technique in a sky-lobby lifting system concept [24]. A sky-lobby lifting system includes two types of cars: shuttle lift cars, which travel only between the main lobby and sky-lobbies, and local lift cars, which only serve their local floors. Their research aimed to find the relationship between different configuration parameters in a sky-lobby lifting system such as the number of shuttles and local lift cars and the sky lobby floor's location.

(iii) *Lifting time calculation algorithms*;

Cho, Lee [17] presented a lifting time calculation algorithm, considering the acceleration and deceleration capacity of the lifting apparatus. They also applied a Branch & Bound algorithm to find an optimal route for a lift car. Koo, Hong [18] introduced a multi-objective optimization model, which aimed to optimize the skyscrapers' lifting logistics to establish a trade-off between time and cost factors, as well as minimizing the electricity consumption, to make the project environment-friendly.

As it was extensively discussed above, the related literature mainly focused on analyzing lift process using scenario based simulations and developing algorithms that can calculate the lifting time. The main objective of the current research is to develop a mathematical model to automatically determine optimum lifting plan for high-rise construction projects.

Unlike previous studies, this research does not investigate different specifications or configuration factors of the lift system by assuming a predefined movement pattern, instead, it tries to find an optimal movement pattern for an already installed lift car in a high-rise construction site.

This model will aid construction managers and decision makers with daily resource (workforce and construction materials) lifting planning process.

3. Lifting operations

Construction projects comprise a high number of repetitive and consecutive activities [25] that demand certain human resource and construction materials. In a high-rise construction project, a significant amount of these activities must be done in a relatively high vertical distance from the ground where there are few means (e.g. tower crane

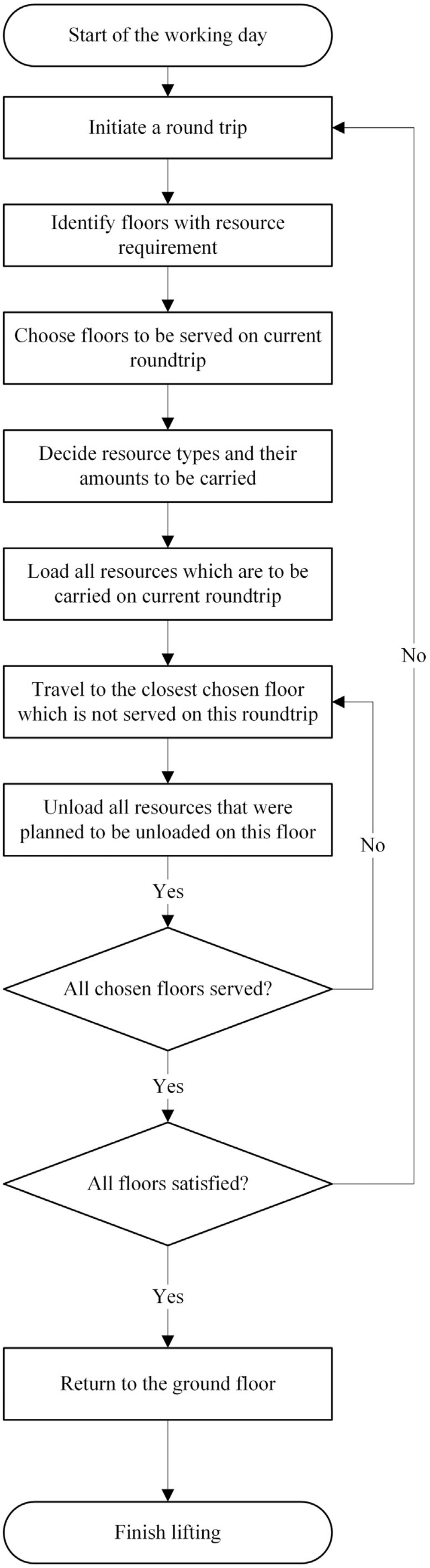

Fig. 1. Lift car operation flowchart.

or lift) for transporting the required resources [26]. In a high-rise construction site where lifts are used for vertical transportation, the workforce productivity highly depends on the performance of the lift cars. There are various factors with possible impact on a lift car's performance including:

- lifting speed
- lift capacity (such as weight and area)
- lift acceleration/deceleration features

Since no zoning [16] or sky lobby system [24] is assumed in this study, the configuration factors including zones, the number of shuttles and local lift cars and the sky lobby floor [2] are not taken into account directly. The other issue that has not been discussed in the literature is lift cars' operation. This issue is mathematically important because any obvious or even arbitrary logic would have a possible impact on optimization model. In this paper, we have extensively studied the introduced lifting algorithm and depicted a generic lift process in Fig. 1. As you can see in this flowchart, at the beginning of a working day, the lift car starts operating. The lift operation process is divided into several round trips, and, each round trip starts and ends on the ground floor. In each round trip, the lift car only changes direction once to minimize the traveling distance. The lift car then continues the supply process through initiating other roundtrips until the whole resource demand of the construction site is satisfied.

In terms of demands for resources in a construction site, the lift operation can be categorized into three operational types that occur at a particular time of the day [17]; (i) lifting only the workers, (ii) lifting only the materials or (iii) lifting both materials and human resources simultaneously. Lifting construction workers typically take place at the beginning or at the end of a working day [16]. These periods of time are considered to be the most critical lifting periods due to a large number of workers that must be lifted by lifts with limited capacities. This bottleneck phenomenon can highly affect the worker productivity in a high-rise construction project, since the time spent on waiting for a lift car or traveling in it does not contribute to the construction progress. The influence of these factors will increase as the buildings get higher and more lifting efforts are needed. To avoid this bottleneck, a traditional solution is to lift the required materials to the demanding floors one or two days before commencement of the planned activities. However, the bottleneck on vertical transportation of human resources still exists [16]. The other recommended solution is to expand the lift working hours and transport construction materials when a site is not operating (e.g. at night) [17,20]. This approach is not applicable in residential areas due to noise restrictions.

At the beginning of a roundtrip of a lift car, the following issues are dictated by the experts: (i) the floors that must be supplied, (ii) the quantity of each material that must be delivered to these floors, (iii) in what order these floors must be served. The lift car starts operating based on this process until the whole demand is satisfied. Fig. 1. demonstrates this process in details.

In this paper, we are introducing an automatic approach to tackle lift process in a high-rise construction site where a considerable number of workforces and materials need to be transported vertically during a day. It must be noted that demand for vertical transportation in practice is not uniform and fluctuates hourly based on active tasks in the project.

4. Methodology

As discussed in the previous sections, an optimal lifting plan is necessary to avoid the delays caused by vertical transportation of materials and workforce in high-rise buildings. In this research, we focus on modeling the lifting process using the graph theory concepts, and, design the lift procedure as a directed weighted graph. Since the direction from which the chosen path is taken, does not affect the total delay, the path is modeled using a directed graph to decrease the computational complexity of the problem.

Directed graphs are made up of nodes and arcs. We assume floors as nodes, and, arcs show routes between floors. An arc that links node *i* to *j* represents a possible route from level *i* to level *j*. In graph theory, there is a well-established concept known as Hamiltonian cycle [27] which refers to a cycle in an undirected graph that visits all vertices exactly once.

The problem of finding the best lifting plan is similar to Vehicle Routing Problem (VRP) [28] in many aspects. The lift car's traveling plan can be seen as a VRP, and each vehicle in the VRP corresponds to a roundtrip in the lift planning problem. The vehicles in the VRP must satisfy the demand of a number of customers, similar to the lift cars. The problem can be assumed more similar to a capacitated VRP [29] since the lift car's carried resources are constrained. The main difference is that unlike VRP, in the lift problem there is no constraint on the number of visits to each node since the demand of each node could exceed the capacity of the car. The other difference is that in this lift problem, only one lift car is assumed and it makes consecutive trips to fulfill the demand of each node. The lift car must serve each level until the level's demand is satisfied and also must visit each level exactly once on each round trip. Lift travels in a cycle since it will return to the origin after serving all of the floors planned for that roundtrip. The shortest traveling path on each roundtrip is obviously the path that includes only one change in the direction of the car. The main difference between the lift planning and similar shortest path problems [28] is the number of nodes visited on each trip. Unlike similar problems [30], in lift planning problem the lift car does not necessarily visit all of the nodes on one round trip. The objective here is to serve all the floors demanding workforce or materials, on consecutive roundtrips. Similarly, a cost is associated with each edge (e.g., the distance), and the main goal is to find a tour with the minimum total cost. However, in the lift planning problem, it is not practical if the objective function is only defined by the total cost of the taken tour. In this paper, a comprehensive objective function is introduced that includes all parameters incurring a cost to the lifting process (e.g. the total number of lift stops, the amount of demanded resources and also the type of resources carried to each floor). In the following section, we will discuss the main components of our model to demonstrate that our introduced platform is not only an optimization tool that minimizes a lift travel cost but also automatically integrates all the key role players affecting the lifting process.

The first stage in creating an operational plan for a lift car is to assemble the data required. Fig. 2 shows the total lift planning process regarding the required inputs and outputs. As you can see in Fig. 2 the parameters, which can affect the operation of a lift car are listed as follows:

1- Lift car's specifications including the speed, acceleration/deceleration, maximum weight, and volume, etc.
2- Site specifications including floor heights and loading/unloading delay for each resource type.
3- Critical and non-critical activities and their assigned resources on the current working day.

In Critical Path Method (CPM), the critical activities are those activities that add up to the longest duration of the project, meaning that they represent the shortest possible duration of the whole project [31]. While planning the lift car's operation, these activities must be prioritized because if their demands are not supplied, the project will be delayed.

These data will input into the platform in order to process and calculate the optimal solution of the lifting plan. The plan, which is generated by the platform, will determine the number of required roundtrips, lift car's path in each roundtrip and the amount of resources carried on each roundtrip.

The planning process of the platform is shown in Fig. 3. As it is shown in this flowchart, the platform decides which path the lift car will take and the quantity of each material that must be transported on each roundtrip. Then the associated costs to each roundtrip are calculated, which regarding the literature [1,2,16,17] has been chosen to be the total lifting time. The platform will calculate the travel time between each pair of floors, using the distances and the lift speed. The speed used here is the average speed of the lift car when not accelerating/decelerating. The fixed delay that each stop imposes to the lifting system can be either entered by the user manually or can be calculated by the platform using the lift car's specification data and a formula presented in [16]. This delay includes the acceleration and deceleration delay as well as door operation delay. The loading/unloading delay of a unit of each resource type is considered in the optimization model and must be input to the platform in order to calculate a more realistic cost function. These amounts can be obtained from an expert or can be measured by on-site inspections for more accurate results.

5. Lift planning process

After acquiring the abovementioned data, the platform primarily calculates the travel time between each pair of floors, using the building geometric information and the lift car's speed. The next parameter that needs to be defined is the *lift delay* at each stop, which can be calculated using lift car specification and the values suggested by the lift manufacturer. Moreover, due to differences in assigned amount/type of materials/workforce on each trip, the loading and unloading durations are dynamically changed. This issue is also being taken into account by the proposed platform while this dynamic pattern in practice is typically determined once by an expert's judgment and is not calculated for each individual round trip. Among the lift parameters, the lift weight and volume capacities are substantially important. The weight capacity is easy to measure and control. However, measuring and control of the space capacity are challenging. Since most resources could not be placed on top of each other, this constraint mainly is determined as the area capacity of the lift car. Then the critical tasks are extracted from the schedule and their planning are prioritized.

After acquiring all the above-mentioned data, the platform is run. The introduced platform basically determines:

(i) Exact traveling path of the lift car in each roundtrip
(ii) Type and amount of material/workforce that must be-be carried by the lift car to each floor of the building

The proposed mathematical model aims to minimize the operational costs of the lift system. The model is discussed in details in the next section.

6. Model development

The following notation is used in this research:

Notations		Symbol	Description
Symbol	Description	W_m	Unit weight of material type m
i, j, k	Floor number indices	A_m	Unit area of material type m
m	Material type index	MD_m	Loading/unloading delay for each unit of material of type n
l	Round trip number index	H_i	Height of floor i
AC	Area capacity of the lift car	C_{ij}	Travel time from floor i to floor j
WC	Weight capacity of the lift car	X_{ijl}	$\begin{cases} 0 \text{ If the path from } i \text{ to } j \text{ is chosen on roundtrip l} \\ 1\ \textit{Otherwise} \end{cases}$
M	A sufficiently big constant	U_{iml}	The amount of unloaded materials of type m at floor i in roundtrip l
SP	Movement speed of the lift car (m/s)	D_{im}	The amount of floor i's initial demand of material m
DL	Average delay caused by each stop (s)	Z	Cost function

Our model follows the following assumptions:

1- Lifting operations take place at critical hours (e.g. start of the working day).
2- There is only one lift car functioning in the site.
3- Each unit of resource takes an amount of time to load/unload depending on the resource type (MD_m).
4- Each stop will impose a constant delay (DL) due to opening/closing the door of the lift car and acceleration/deceleration process.
5- The speed of the lift car is assumed to be constant (SP).
6- The amount of materials loaded on the lift car on each roundtrip is constrained by the weight capacity and the available area of the car.
7- The resources are located on the ground floor with $i = 1$.

Then based on the above assumption, the following formulation is introduced to optimize the lifting process:

$$Min \sum_i \sum_m \sum_l MD_m * u_{iml} + \sum_i \sum_j \sum_l (DL + C_{ij}) * x_{ijl} \tag{1}$$

$$\sum_i \sum_m u_{iml} * w_m \le WC \qquad \forall\ l \tag{2}$$

$$\sum_i \sum_m u_{iml} * A_m \le AC \qquad \forall\ l \tag{3}$$

$$\sum_i x_{ijl} \le 1 \qquad \forall\ j, l \tag{4}$$

$$\sum_{i,i>j} x_{ijl} = 0 \qquad \forall\ j > 1, l \tag{5}$$

$$\sum_i x_{ijl} = \sum_k x_{jkl} \qquad \forall\ j, l \tag{6}$$

$$\sum_m u_{jml} \le M * \sum_i x_{ijl} \qquad \forall\ j, l \tag{7}$$

$$\sum_l u_{iml} \ge D_{im} \qquad \forall\ i, m \tag{8}$$

$$M * \sum_{i=1} \sum_j x_{ijl} \ge \sum_j \sum_m u_{jml} \qquad \forall\ l \tag{9}$$

A lift system is expected to transport materials and workforce to the assigned levels on time and with minimum delays, so in this paper, our objective function (Eq. (1)) is designed to cover three types of delays;

(i) loading and unloading times ($\sum_i \sum_m \sum_l MD_m * u_{iml}$).
(ii) stop delays imposed at different levels ($\sum_i \sum_j \sum_l DL * x_{ijl}$)
(iii) the lift car's traveling time ($\sum_i \sum_j \sum_l C_{ij} * x_{ijl}$).

The term C_{ij} represents the travel time between each two floors and is calculated as follows:

$$C_{ij} = \left| \frac{H_j - H_i}{SP} \right| \tag{10}$$

The constant delay itself is affected by the door opening and closing time and acceleration/deceleration delay. In lifting time calculation algorithms presented in the literature, acceleration and deceleration times are precisely calculated. In this study however, the purpose of the model is not to calculate the exact travel time. Since the main purpose of this model is to find the best travel path, we assume both travel speed and delay at each stop to be constant. Regardless of this issue, implementing the available formula for calculating the dynamic pattern of lift speed will impose an excessive complexity to the formulation, which may reduce the chance of obtaining the optimum solution within polynomial time. However, this does not mean that we have compromised on accuracy to obtain a relaxed optimum solution; the introduced cost function (Eq. (1)) is a good approximation of the real delay and travel intervals. It also covers all three main delay functions in a typical lift system. In details, the first term ($\sum_i \sum_m \sum_l MD_m * u_{iml}$), in Eq. (1) covers material loading/unloading delay which does not actually affect the optimization process and has only been included to calculate a good approximation of the total amount of delays. The second term ($\sum_i \sum_m \sum_l U_{iml}$), will not vary since it has to be greater than or equal to the initial demands according to Eq. (8) and it is subjected to minimum travel delays. So, if it is not intended to have an approximation of the total delay, then the first summation in the cost function can be eliminated.

Eqs. (2) and (3) restrict the amount of materials carried on each roundtrip, regarding the weight and area capacity of the lift car. The role of Eq. (4) is to prevent more than one entry to each level (node) on each roundtrip. Meaning that it is not optimal for the lift car to make two stops on the same floor on a roundtrip. Eq. (5) is also introduced to ensure the lift car is allowed to storage level if and only if it has unloaded all of the materials it has been carrying. The lift visits the storage on the ground floor only after its direction changes to downwards. Eq. (6) is introduced to ensure the flow conservation that means the

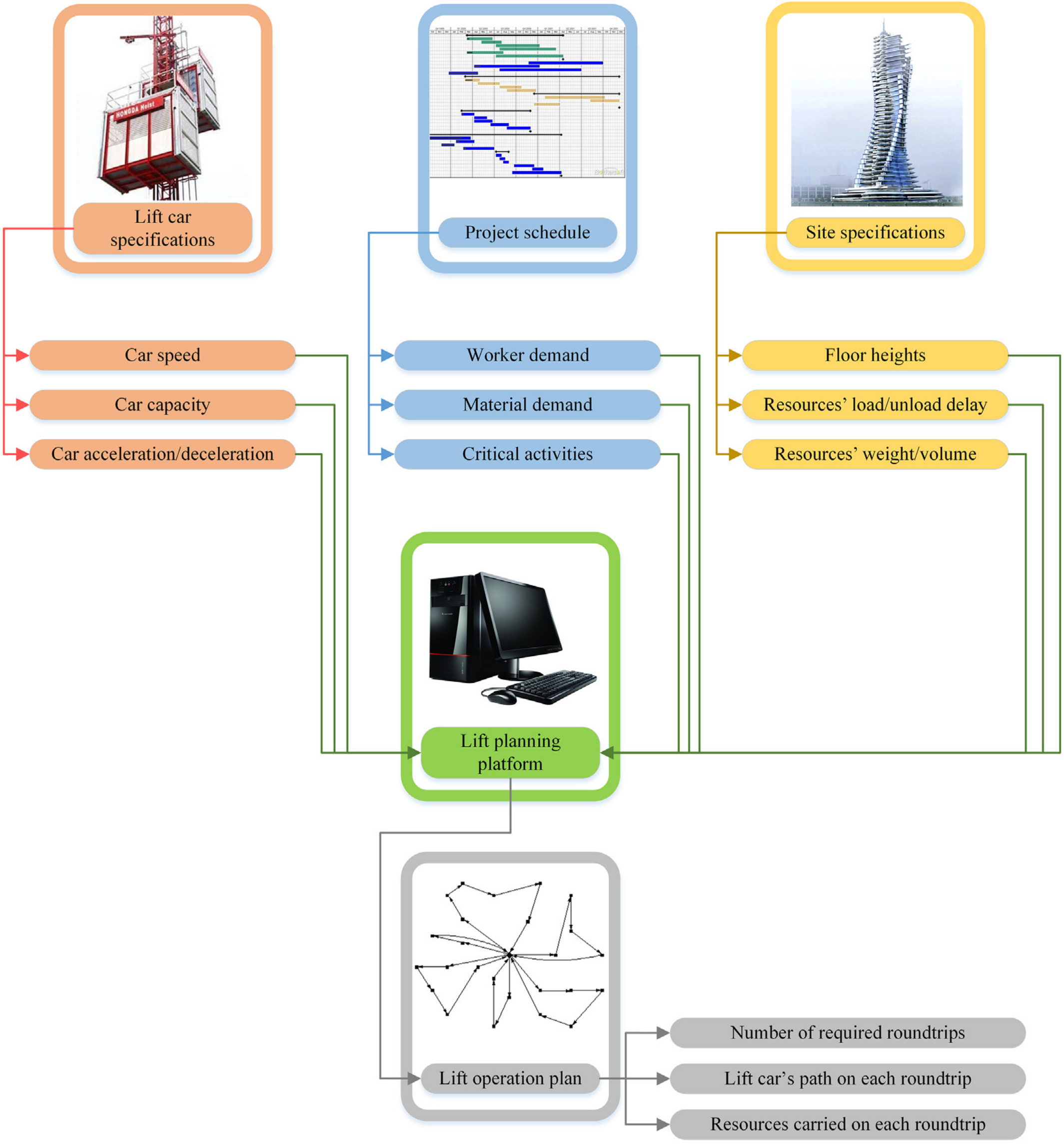

Fig. 2. Construction lift planning process.

number of arrivals at each floor is equal to the number of departures. Eq. (7) forces the number of unloaded materials at a floor to be zero, if the floor is not chosen to be visited by the lift. Similarly, the total amount of unloaded materials on each floor must be greater than or equal to the total demand of that floor, as restricted by Eq. (8). Finally, since each tour does not include all nodes, Eq. (9) must be added in order to include the storage on each round trip. The equation simply means that if there is an unloading operation on the current roundtrip, then the storage floor must be chosen as a stop on the lift car's path.

According to the problem formulation presented above, the main physical effect of the model on the lift car's operation is minimizing the total traveling time of the lift car. The proposed model considers both weight and area capacities of the lift car as constraints, while trying to minimize the total number of round trips and the total stops. The model can determine the combination of resources that must be transported vertically on each roundtrip while considering the maximum lift utilization. Also, the lift car's operation process has been thoroughly defined in the model. Therefore, the model outputs are practical decisions that ensure minimum delays during the lift operation process on a day.

An example of the total travel path of the lift car is presented in Fig. 4. Each color in this graph indicates a roundtrip. The large node in the middle represents the storage located on the ground floor. Other nodes represent higher floors of the building. Each set of arcs with the same color represent a roundtrip in the lift car's path. As it is seen in this figure, the network upholds the conservation on each roundtrip. Each roundtrip starts and ends on the storage floor and there is no constraint on the number of visited nodes on each roundtrip. Each node can be included more than once in the lift car's path in consecutive roundtrips. The number of floors served on each roundtrip highly depends on the lift car's area/weight capacity, floors demands and the demanded resources' properties.

6.1. Subtour elimination

For the introduced model, still a mathematical challenge exists which is the presence of subtours. A subtour is a cycle in which the

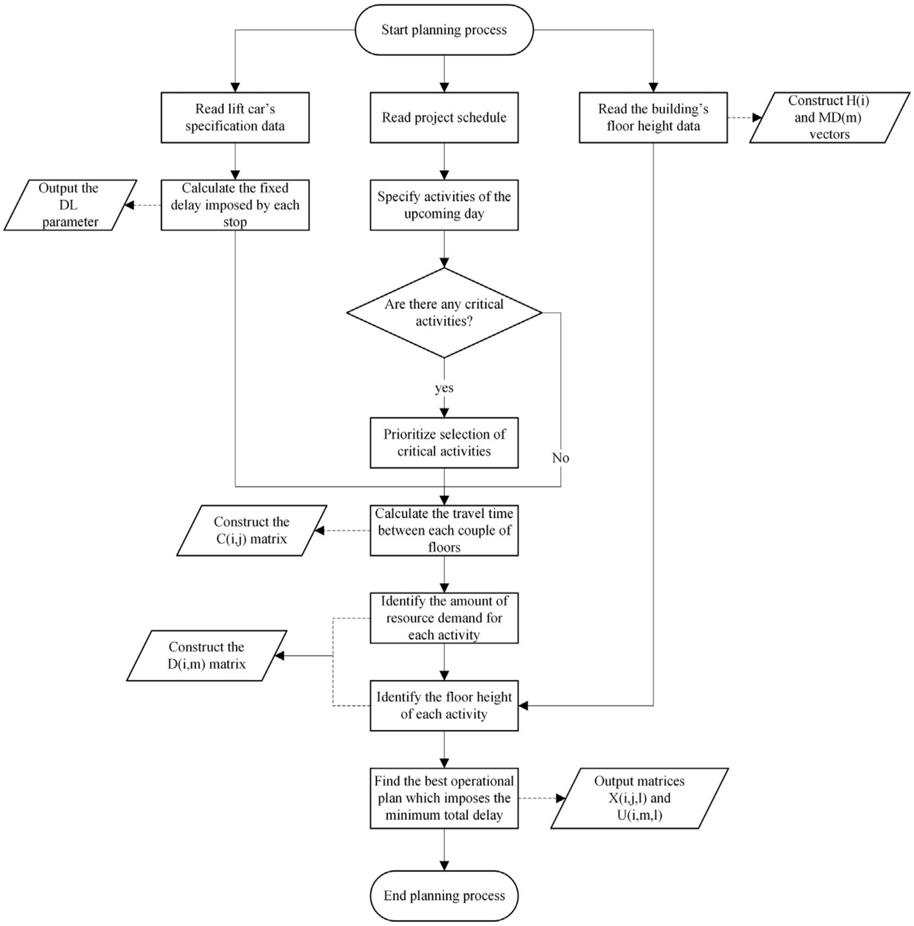

Fig. 3. Construction lift planning flowchart.

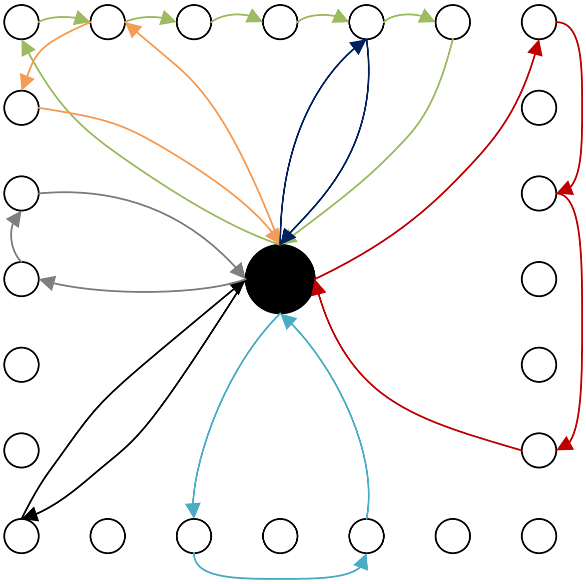

Fig. 4. An example of the lift car's travel path.

origin is not included. The subtour will not violate the initial conditions of the model while the path visits each node exactly once and includes all of the nodes. The only difference is that there is more than one cycle in the path. Fig. 5, is devoted on illustrating the subtour concern. The ordinary subtour in a graph is shown In Fig. 5(a). as it can be seen in this figure, each vertex is visited only once in this undirected graph, but the whole path coqntains more than one cycle, which is not feasible in an optimal route problem. Fig. 5(b) illustrates the subtour in a lift car optimization. In this figure, the red arc makes the subtour infeasible, because this arc adds an extra direction change to the roundtrip. Restricting the movement path of the lift car in this manner will highly decrease the size of the solution space and increases the computational complexity.

Several formulations have been proposed in the literature for subtour elimination purpose (such as [32,33]). In these formulations, mainly it is required to know the total number of the vertices in advance. The number of nodes in lift car optimization problem reflects the number of floors visited on each roundtrip, which is a decision variable and needs to be optimized. To avoid having subtours we adopted another approach, which is adding an extra constraint to the problem (Eq. (5)). According to this equation, only one direction change is allowed on each round trip. In the case of a vertical transportation problem, only one dimension (vertical) exists and the location vector has only one scalar component, which is the height of each floor. So, in order to eliminate the subtour, the variable x_{ijl} is restricted to zero if the destination is located in a lower place than the origin. This constraint is defined on the set of all floors except the ground floor, since the lift car must be allowed to return to the storage once on each roundtrip.

7. Case study

In this section, the introduced platform for optimizing the lift

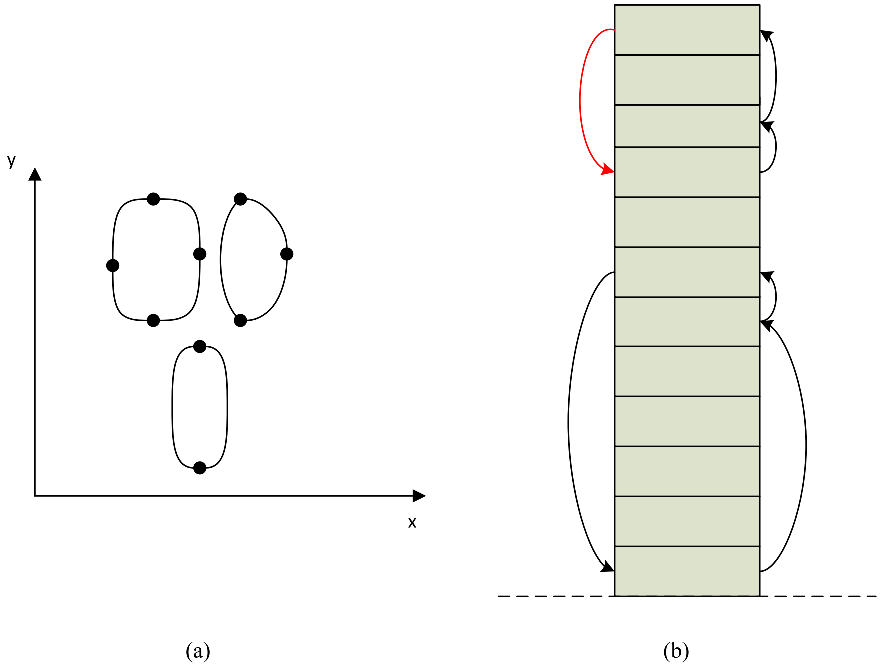

Fig. 5. An example of subtours in TSP (a) and in a building (b). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1
Lift car specifications.

Characteristic	Value
Speed	36 m/min
Weight capacity	1500 Kg
Dimension	2.5 × 1.5 × 2.1 m^3
Area capacity	3.75 m^2
Constant delay	30 s

Table 2
Resource characteristics.

Resource type	Weight (kg)	Occupied area (m^2)	Loading or unloading delay (s)
Staff	85	0.28	3
Gyprock	35	0.5	10
Office doors	80	0.45	15
Pipes	15	0.1	7

Table 3
Building data on heights and demands.

Floor	Height (m)	Material demand			
		Workforce	Gyprock	Office door	Pipe
1–25	–	–	–	–	–
26	109.8	4	14	9	–
27	113.6	4	14	9	–
28	117.4	4	14	9	–
29	121.2	–	–	–	–
30	125	–	–	–	–
31	128.8	–	–	–	–
32	132.6	6	–	–	8
33	136.4	6	–	–	8
34	140.2	6	–	–	8

problem is evaluated using field data obtained from a high-rise construction project. The data collection from high-rise construction projects is a challenging and cumbersome task due to privacy concerns of the builders. Therefore, in this study, we have tested only a single set of data that acquired from a 34-story construction project. Armitaj building in Mashhad, Iran has been chosen to test our platform, which is a 34-story commercial building with total area of 20000 m^2 and 140 m height. Currently the project is in the finishing phase and the stakeholders are demanding the delivery of the project as soon as possible. The technical specifications of the lift car are presented in Table 1. The inner dimensions of the lift car are 2.5 m × 1.5 m × 2.1 m (length ∗ width ∗ height). It also must be noted that the height of each floor is assumed to be the height of the deck of that floor. According to the project manager, the most critical time of the day regarding lifting operation is the morning peak hour. To implement the optimization model in this project, three types of information are needed; (i) lift car specifications (e.g. speed, dimension, weight capacity, door operation time and acceleration/deceleration delay), (ii) project schedule information (current activities, workforce demand, material demand and critical activities) (iii) building specifications (floor heights).

In a day selected by the project manager, three main activities are identified such as gyprock installation, office door installation and pipefitting. The according demand for vertical transportation is summarized in Table 2.

An average weight of 85 Kg is assumed for a worker, considering the extra weight of their tools and equipment. The gyprock board has a dimension of 1.2m × 2.4m × 1.25mm and will approximately take up 0.5m^2 of area if placed appropriately in the lift. The office doors are not identical and may have different weights and dimensions considering their types. The geometric and weight features of the doors are extracted from the approved shop drawings and then are fed to the model. The required pipes are typically supplied to the site in length of 6 m, and therefore do not fit inside the lift car. A small hole embedded in the roof of the lift car is, thus, used to allow fitting pipe spools in the lift car. The number of pipes, which will fit in the lift car, will be limited to four, and therefore, another constraint will be added to the formulation as follows:

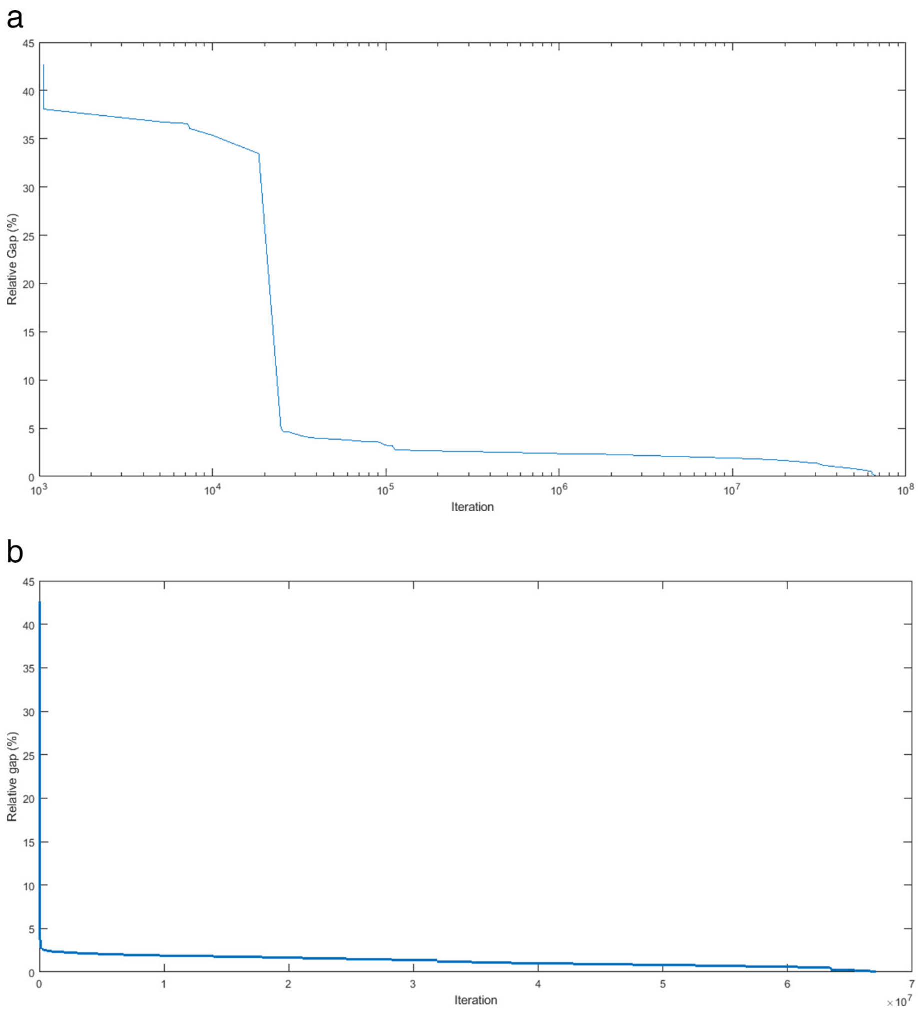

Fig. 6. .A Semi-logarithmic convergence curve of the optimization process (iteration-gap).
Fig. 6.B Linear convergence curve of the optimization process (iteration-gap).

$$\sum_i U_{iml} \le 4 \qquad \forall\ l,\ m = pipe \tag{11}$$

This also shows the resilience of our model in dealing with customized lift demand. Other detailed information on the demanded materials is summarized in Table 3.

All of the required data are acquired and stored in a database. The main core of the formulation introduced in Section 5 is implemented on CPLEX/GAMS. The system used for this purpose has a 2.67 GHz Intel core i5 430 M processor with 4.00 GB RAM and a Microsoft Windows 8.1 Operating system.

Adding the extra constraint for the pipes to the problem, highly increases the computational complexity of the problem. The optimization computing process is illustrated from different angles. In Figs. 6 and 7 in the form of convergence curves. The horizontal axis is presented in a logarithmic scale to give a better visual representation of the calculation process in Figs. 6.A and 7.A. Figs. 6.B and 7.B illustrate the curve of the iterations and elapsed time against relative optimality gaps of the solution respectively.

Table 4 shows a summary of the solution of the problem with a relative gap of 0% obtained in 3720 s. Each column in this table represents a roundtrip, and each row represents a resource type carried to a specific floor. The value reported in each cell indicates the number of resources carried to a specific floor. The floors, which are visited by the lift car on a round trip, are shown with a thick border. It must be noted that the floors are visited by the lift car from the lowest to the highest.

In the literature, [17] it is claimed that in round trips including multiple stops, having stops every 3–5 floors is optimal. We can see the number of floors it travels until the next stop, in the last row of Table 4.

X_{ijl} and U_{iml} are the two main outputs of the model. Both of these variables contribute to showing the optimal plan in the problem, so they must be combined and shown in a single table such as Table 4. As you can see in this table, the optimization has tried to minimize the number of visits to the higher levels (i.e. 32, 33 and 34) and made only two trips to each of them, while it made four trips to each of the lower levels (i.e. 26, 27 and 28).

The other notable result in the optimal lifting plan, is that the lift car carries various material types on each roundtrip in order to make the minimum number of stops (Fig. 8). Therefore, the number of stops made on each roundtrip is limited to two. It can be logically inferred that this number can vary depending on the resource properties and the

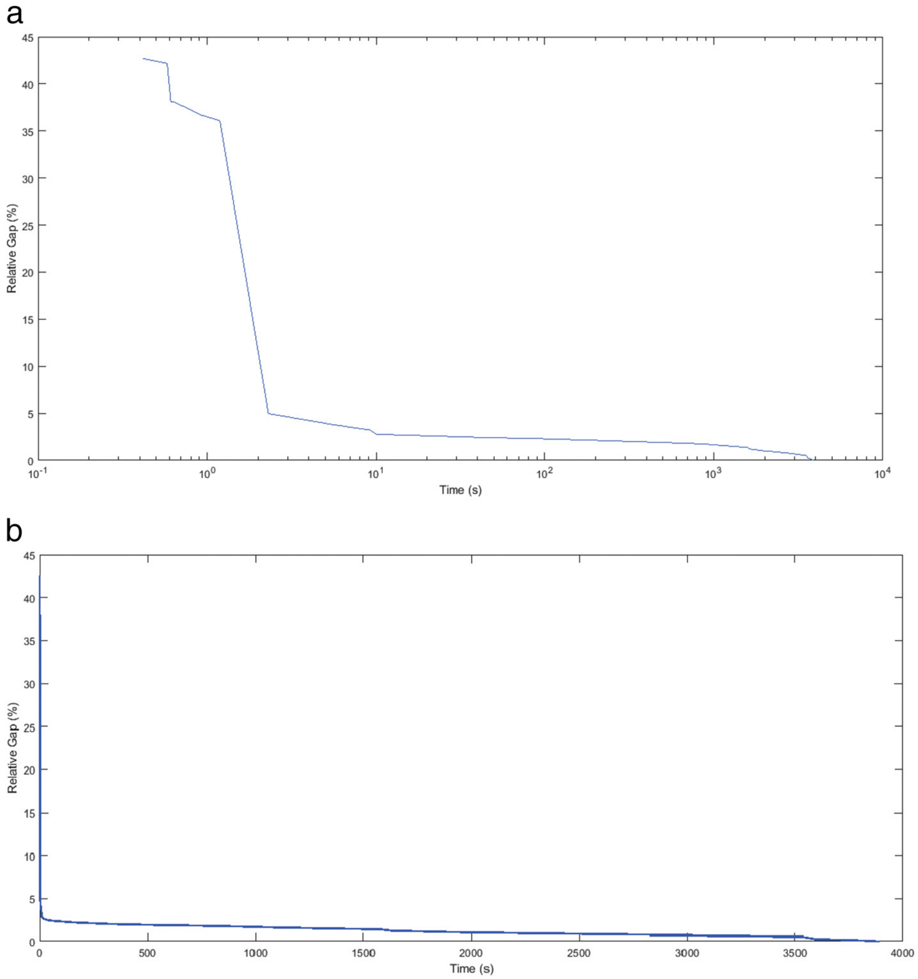

Fig. 7. .A Semi-logarithmic convergence curve of the optimization process (time-gap).
Fig. 7.B Linear convergence curve of the optimization process (time-gap).

demand of each floor.

In the optimal lifting plan obtained, the dominant capacity constraint is the area constraint in all roundtrips. As it is shown in Table 5, the total area used up in each roundtrip is higher than 3.5 m^2 in almost all roundtrips. This phenomenon is caused by the high inherent volume of the material types used in the finishing stage of this building.

The presented model generates the optimum operational plan in a high-rise construction site with already installed lifting equipment. In the literature, the number and the optimal specifications of a lift car, as well as the optimal lifting plan in predefine scenarios (such as zoning and sky-lobby systems), have already been studied using simulation-based techniques [1,2,16–18]. In this research however, we neither assume a scenario nor try to find the optimal specifications of the lift system. Given a high-rise construction site with an already installed lift car (which can be chosen using the previously introduced techniques), this model will find the best movement pattern for lift operation process which imposes the minimum operational cost and avoids unwanted vertical transportation delay to the project.

8. Conclusion

Vertical transportation of materials and workforce is a bottleneck in high-rise building construction projects. In a high-rise construction project, the required workforce and materials for a large number of repetitive and consecutive activities must be supplied within a short time window, while only a few practical solutions for vertical transportation exist including tower cranes and lifts. Tower cranes are an important means of horizontal transportation as well as vertical. The lift system is, therefore, a more reliable solution for the vertical transportation purpose, since it is not used for other purposes and its vertical reach can be extended, unlike tower cranes.

It was discussed in the literature that the morning peak hour is the most crucial period for the lift system. In high-rise building construction projects, it is common to lift the required materials a couple of days in advance or the night before the activity begins, but it is not possible to transport the workforce in this manner. Also, on some construction sites, it is not possible to lift materials and equipment far prior the tasks' commencement. Due to high inherent complexity of the construction activities of a high-rise building, it is difficult to optimize the resource

Table 4
The amount of unloaded resources of each type at different floors for each roundtrip.

Floor Number	Resource Type	Round Trip Number											
		1	2	3	4	5	6	7	8	9	10	11	12
26	Staff		4		0			0			0		
	Boards		5		0			7			2		
	Doors		0		3			0			6		
	Pipes		0		0			0			0		
27	Staff			0			0			1			3
	Boards			5			2			3			4
	Doors			0			6			1			2
	Pipes			0			0			0			0
28	Staff	4				0			0			0	
	Boards	5				0			5			4	
	Doors	0				6			0			3	
	Pipes	0				0			0			0	
32	Staff			3					3				
	Boards			0					0				
	Doors			0					0				
	Pipes			4					4				
33	Staff					2				4			
	Boards					0				0			
	Doors					0				0			
	Pipes					4				4			
34	Staff				6							0	
	Boards				0							0	
	Doors				0							0	
	Pipes				4							4	
Floors Traveled		0	0	4	7	4	0	0	3	5	0	5	0
Number of Stops		1	1	2	2	2	1	1	2	2	1	2	1

transportation of the morning peak time and avoid the bottleneck phenomenon. In order to tackle this problem, a mathematical model for the operational plan of a single car lifting system is presented in this paper, which aims to minimize the lift car's total travel time. This issue will result in more worker productivity and better construction progress.

The quality of the optimization model depends on the comprehensiveness of the input data, which is fed to the model. Rather than the optimization model, an integrated platform was introduced that collects and consolidates the following information from the appropriate resources: (i) lift specification, (ii) project schedule and (iii) building specification.

Unlike most of the models presented in the literature, the platform proposed in this study optimizes the operational process of a lift car in a high-rise construction project. The model was tested using field data gathered from a 34-story commercial building. The results show that the model could find a solution with 0% optimality gap in approximately 1 h, which is an acceptable amount of computational cost for the problem. The proposed model can handle lift process planning by considering practical aspects of this problem, and optimizing this process based on a mathematical procedure. Since this optimum finding process is based on a mathematical procedure, the optimal solution is guaranteed to be the global optimum. Optimizing the lifting process not only decreases the construction delays, but also reduces the operational costs of the lift car.

The following topics could be subject of future studies:

1- Optimization of a multiple car systems with different lifting equipment properties.
2- Developing a stochastic model for dealing with uncertainties of demand.
3- Development of a mathematical model, which takes into account both tower cranes and the lift cars.
4- Finding the optimum number of lift cars for the entire construction phase of a high-rise project.

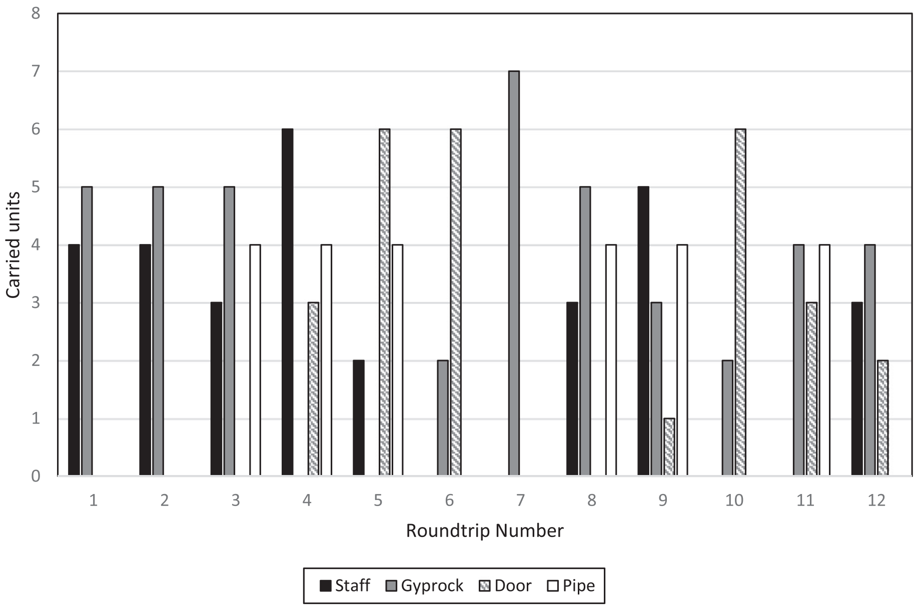

Fig. 8. Optimal number of each resource type, carried on each roundtrip.

Table 5

A comparison between two capacity constraints.

Roundtrip number	1	2	3	4	5	6	7	8	9	10	11	12
Total weight carried (Kg)	515	515	490	810	710	550	245	490	670	550	440	555
Total area used (m^2)	3.62	3.62	3.74	3.43	3.66	3.7	3.5	3.74	3.75	3.7	3.75	3.74

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