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How many lifts does a construction site need? A Global optimization approach

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Abstract

Purpose – Due to the expansion of high-rise construction, construction machinery, especially lifts, has become essential in building projects. Therefore, this paper presents an optimal lift configuration considering the lift's daily rental, operational, horizontal material handling costs and penalties for material delivery delays for better cost management.

Design/methodology/approach – The proposed method divides the project into several stages based on the required materials. Then, a novel Mixed-Integer Linear Programming model (MILP) is developed to find the best type, number and location of lifts at every stage. It can accommodate any variation in location, numbers and type of lifts during project execution. The developed model also considers the costs of lift dismantling and installation to avoid additional expenses.

Findings – The developed mathematical model is tested using field data from a real-world application to demonstrate its ability to minimize project costs and working days. The results indicate that modeling all stages simultaneously while considering installation and dismantling costs reduces project costs by 3.7%. Moreover, including horizontal material movement cost in the objective function has resulted in a 40.8% cost savings, and considering the delay penalties has also reduced the overall project costs by 44.8%.

Originality/value – This study extends the previous approaches by addressing critical yet underexplored factors, such as the number and location of lifts in a construction site, as well as considering dynamic changes in construction material requirements and delay penalties in a novel mathematical model based on pre-determined timeframes. Unlike most of the similar studies that have focused on simulation tools or heuristic methods to determine the best solution for lift location problems in a construction project, this paper aims to determine a global optimum solution while trying to provide a more practical framework by considering influencing factors that have not been adequately addressed before in the similar studies.

Keywords Lift layout, Construction, Optimization, Location problem, Site layout planning

Paper type Research article

1. Introduction

With the growth of urbanization, high-rise construction has become one of the most important approaches for alleviating the shortage of available land (Huang *et al.*, 2010; Shin *et al.*, 2011). The most important issues related to high-rise construction revolve around effective material transportation (Zhang and Pan, 2020; Kim *et al.*, 2016). Applying hoists and tower cranes has become inevitable for vertical and horizontal material transfer at the construction site (Park *et al.*, 2013; Hwang, 2009). Specifically, lifts primarily provide vertical transportation for lighter materials and personnel (Hwang, 2009; Jung *et al.*, 2017a), while tower cranes are responsible for the horizontal and vertical movement of heavier loads (Park *et al.*, 2013; Ahmadnia *et al.*, 2025). Accordingly, as the construction project advances, tower cranes' access to building floors becomes restricted, emphasizing the importance of lift usage (Cai *et al.*, 2016).

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The optimal arrangement of tower cranes and lifts can considerably affect project costs (Tariq *et al*., 2022; Al Hattab *et al*., 2018; Zhang *et al*., 2022; Xu *et al*., 2020). While there are many studies related to the proper positioning of tower cranes, the issue of determining the most suitable configuration of lifts has been given relatively less emphasis. Several researchers, including Zhang *et al*. (1996), Tam *et al*. (2001), Tam and Tong (2003), Huang *et al*. (2011), Moussavi Nadoushani *et al*. (2017), Huang and Wong (2018) and Amiri *et al*. (2023) focused on determining the optimal location of a single-tower crane. This challenge has also been dealt with by Zhang *et al*. (1999), Lien and Cheng (2014), Ji and Leite (2020) and Wang *et al*. (2015) within the framework of optimizing multiple tower cranes.

Moreover, some researchers, such as Yeoh and Chua (2017), Wu *et al*. (2020a), Dienstknecht (2023), Marzouk and Abubakr (2016) and Ahmadnia *et al*. (2025) were able to specify the type, number and location of tower cranes simultaneously. Lin and Haas (1996) presented an integer programming model to optimize crane configurations and placements for multiple heavy lifts on a construction site. Also, Moselhi *et al*. (2004) addressed the locations of mobile cranes. The literature has studied the optimum arrangement of lifts comparatively with less attention. The current research aims to fill this gap by defining the problem of lift layout and emphasizing its significance and challenges in high-rise construction logistics.

Material transportation in a high-rise construction site usually contains multiple steps. First, the workers relocate the required materials from the depot areas to the lift installation location and load them into the lift. Second, the workers carry the materials up to the desired floor by lift. Third, the workers unload the materials from the lift and move them to specific demand points within the floors. Since horizontal movements of materials within the floors are difficult and expensive (Matsuzaki *et al*., 1999), an appropriate optimization of the construction lift setup can reduce the travel distance of the workforce for horizontal movements. In addition, access to specific demand locations will be restricted during the project execution due to internal and external wall implementations or because of the multi-part nature of the building on some floors.

The arrangement and placement of construction lifts directly influence costs and construction time. Their layout, in particular, considering the limitation brought about by the structure under construction, enhances the efficiency of the workforce and accelerates the progress of the project. For example, these installation locations can be evaluated for structural integrity using shoring and reshoring methods (Shehadeh *et al*., 2024a). These selected locations for lift installation should preferably not be near electrical and mechanical facilities in order not to cause seepage of water through pipes (Almasabha *et al*., 2024). Furthermore, to facilitate the unloading and storage of materials, it is advisable to avoid selecting storage locations near high-traffic and high-speed areas. This will enhance worker safety and minimize the time required for material unloading (Almadi *et al*., 2023). Structural changes at lift installation locations should be regularly inspected using methods such as Slope Displacement Inspection and Management algorithms (Shehadeh *et al*., 2024b), Markovian frameworks and multi-tiered exponential erosion risk models (Shehadeh *et al*., 2024c) and Predictive Maintenance (PdM) strategies (Alshboul *et al*., 2024).

Construction lifts can differ by the amount of their loading capacity and movement speed. The use of lifts with lower speed and capacity might result in a longer project duration and working days (Yun *et al*., 2021) and increase the time required for the vertical transportation of materials (Wu *et al*., 2020b). This can lead to higher costs related to labor wages and rental costs of construction equipment. Using faster, higher-capacity lifts could be a possible solution to this problem. However, using high-performance lifts is more expensive (Shin *et al*., 2011; Wu *et al*., 2020b). Therefore, selecting the best sort of lift for a particular building project can be an important task and needs to be selected with extreme care. A proper selection of the most suitable lift configuration according to speed, capacity and cost is so vital that it can effectively balance efficiency in the project while reducing the overall expenditure.

Another possible way of shortening the project duration and minimizing the distance that laborers needed to travel for horizontal material movement could be increasing the number of lifts. However, the overall costs related to renting, maintenance (Ng *et al*., 2023; Niu *et al*., 2021), installation and dismantling (Kim *et al.*, 2018; Jung *et al.*, 2017b) may increase with increased numbers of installations. Moreover, because of space limitations, the number of lifts installed within the job site cannot be excessive (Cho *et al.*, 2013; Cho *et al.*, 2011). Therefore, the simultaneous optimization of lift type and number can be a better option to decrease project costs and allow efficient horizontal transportation of materials among floors. The required materials for the demand points can be estimated in advance before the execution of the project (Wu *et al.*, 2020b). However, the type and quantity of these required components might change during project execution (Park *et al.*, 2013; Jalali Yazdi *et al.*, 2019). So the project can be divided into different stages according to daily altering requirements (Riga *et al.*, 2020). Due to changing requirements, the optimal layout of lifts (including the number, type and optimal location) may change at each stage. However, in the case of changing the type and location of lifts during the project, higher installation and disassembly expenses may result (Matsuzaki *et al.*, 1999). The main challenge is to find an optimal layout for all construction stages that reduce overall project costs.

Given the complexities and challenges associated with material transportation in high-rise construction, mathematical optimization models play a crucial role in determining the optimal layout of lifts. However, no optimization model has yet been developed to address this specific issue. To fill this gap, this paper proposes a mixed-integer linear programming (MILP) model aimed at optimizing the type, number and location of lifts required for construction projects. The main objective of the proposed approach is to minimize total cost, which involves the cost of renting, maintenance, installation and dismantling of lifts, the workers' wages and working days. The proposed model considers the dynamic material requirements of the construction project by dividing the project into various stages with particular material needs. The arrangement of lifts is reassessed at the start of each stage considering the changing demands and also to avoid unnecessary installation and deconstruction of lifts. The model specifies the required working days for each stage within the given timeframe. In essence, this means the material needs of each stage should be fully satisfied on time. The model optimizes scheduling requirements by introducing a penalty for delays in the objective function where the supply of material cannot be achieved within the specified time. It also determines lift locations to minimize the horizontal movement of materials by workers across the floors. This reduces the time and cost incurred in such movements. Such an integrated method offers the best arrangement for the lifts that maximize efficiency in the whole material transportation process in the construction. Model efficiency is tested on a real case study which demonstrates its effectiveness and cost optimization.

2. Literature review

Extensive research has been conducted to make more effective use of the building lifts. The scientific efforts can be principally classified into two major categories: (1) Lift operational planning including scheduling and routing lift(s) to meet daily material demands (e.g. Jung *et al.*, 2017a; Cho *et al.*, 2013; Jalali Yazdi *et al.*, 2018; Jalali Yazdi *et al.*, 2019; Shin *et al.*, 2018; Chen *et al.*, 2024); and (2) Lift layout including the determination of the number, type and location of lifts needed for the project. As the proposed method in this paper is about lift layout, some relevant research on the topic is discussed further.

Hwang (2009) tried to determine the variables involved in the layout of construction lifts by using a questionnaire. The work is based on the view of experienced personnel. Using the results obtained from his questionnaire, he simulated lift operations to obtain the configuration of choice. In another work, Hwang (2015) presented an analytical approach – a method that employs mathematical models to systematically evaluate the effectiveness of various lift design configurations – for evaluating the effectiveness of different configurations of lift design.

Shin *et al.* (2011), using simulation and genetic algorithms, computed the optimum type and amount of lifts required for a construction project. In that paper, an optimal solution was searched by using a genetic algorithm and then the results were verified by using simulation.

Ruokokoski and Siikonen (2017) assessed the effective handling of load peak time in determining the number and type of lifts. They first designed different scenarios and then selected the best layout out of the available options. Kim *et al.* (2020) zoned the floors of a building first and then used simulation to determine the number and type of lifts required. Yun *et al.* (2021) incorporated rental cost and travel speed as important variables in their simulation-based methodology to determine the number and type of lifts a project would need.

The effect of lift location on the horizontal amount of movement by workers is one of the important considerations that were not taken into account in previous studies. Matsuzaki *et al.* (1999) used a heuristic technique – a combination of genetics and simulated annealing – a method inspired by the cooling process of metals to find optimal solutions – to minimize such horizontal material movements. The developed algorithm considers the installation cost of the lifts and horizontal and vertical material handling costs in its selection for the number and locations of the lifts. In this respect, Abdelhafiez *et al.* (2007) focused on reducing horizontal movements, taking into account the Euclidean distance – the straight-line distance between two points in space – of the material flow patterns.

The optimal layout of material depot locations (supply points) can help to reduce horizontal movements, as demonstrated by the genetic algorithm approach of (Fung *et al.*, 2008) and the mixed-integer programming model and genetic algorithm proposed by Huang *et al.* (2010). Huang and Wong (2019) further suggested a binary mixed-integer programming technique for locating supply points to reduce horizontal movements and the overtime cost associated with this. The solution of their optimization model was performed with a branch-and-bound approach – a method that divides the problem into smaller parts and calculates bounds to eliminate suboptimal solutions. Where these studies focused on optimizing the location of supply points to reduce horizontal material flows, the locating of building lifts may have an even more substantial effect in minimizing horizontal movements at both supply and demand points. This paper focuses on the precise placement of building lifts to minimize horizontal material movements on the construction site.

Table 1 provides an overview of the existing research on lift layout optimization.

This review highlights the absence of an optimization model specifically designed for determining the optimal location of lifts in construction projects. Optimization models may provide more economical solutions compared to simulation and heuristic techniques in practical cases. Therefore, this research proposes a MILP model for the lift layout problem in construction. The model proposed attempts to find the most appropriate location, number and type of lift needed to be used on the construction site so that the horizontal material handling cost is minimized as well as the rental and operational cost of the lifts. Furthermore, the proposed model considers a variation in material demand during different stages of the building. In that case, the model optimizes the cost of installing, dismantling and renting of lifts. Besides, there is a penalty in the objective function due to delays in material supply.

3. Proposed method

This section presents a MILP model for finding the optimum planning of lifts at a construction project. The major objectives of this model are to find the optimal number, type and location of lifts that will minimize the overall number of working days and construction costs. Furthermore, it tries to optimize the horizontal material movements of workers by minimizing the distance and time spent conveying the materials between floors. The proposed model optimizes the installation and dismantling costs of the lift, because of the changes in required materials during project implementation. The assumptions of the proposed model are as follows:

(1) A building can have positive or negative floors.

(2) The candidate locations for lift installation are predetermined.

Table 1. An overview of the existing research on lift layout optimization

	Method			Lift					Objective function Costs				Penalties
Paper	Simulation	Heuristic	Optimization	Number	Location	Type	Supply point location	Construction stages	Operation	Rental	Horizontal movement	Installation and uninstallation	Daily
Hwang (2009)	✓			Variable	Variable	Variable	Fix						
Shin *et al.* (2011)	✓	✓		Variable	Fix	Variable	Fix			✓			
Ruokokoski and Siikonen (2017)	✓			Variable	Fix	Variable	Fix		✓				
Kim *et al.* (2020)	✓			Variable	Fix	Variable	Fix		✓	✓		✓	
Yun *et al.* (2021)	✓			Variable	Fix	Variable	Fix						
Matsuzaki *et al.* (1999)		✓		Variable	Variable	Fix	Fix				✓	✓	
Abdelhafiez *et al.* (2007)	✓			Multiple	Variable	Fix	Fix				✓		
Fung *et al.* (2008)		✓		One	Fix	Fix	Variable				✓		
Huang *et al.* (2010)		✓	✓	One	Fix	Fix	Variable				✓		
Huang and Wong (2019)			✓	One	Fix	Fix	Variable				✓		✓
Proposed Method			✓	Variable	Variable	Variable	Fix	✓	✓	✓	✓	✓	✓

Source(s): Authors' own work

(3) Lifts differ in movement speed, cabin dimensions, lifting capacity (volume–weight) and cost of use (including rental, operation, installation and dismantling).

(4) The construction operation is separated into several stages. Construction stages can be different in the type and quantity of required materials as well as the candidate locations for lift installation.

(5) Material requirements for various floors of the building are pre-estimated for every stage of the building process. The lifts must completely satisfy these requirements before the completion of each stage.

(6) The construction operations also allow the modification in the lift(s) type and their location of installation. This further leads to the installation and de-installation of lift (s) during the construction operations. To optimally control these changes, the cost of installation and uninstallation of the lift(s) has been considered by the proposed model.

(7) All materials are deposited on the ground floor of the building. As a result, the ground floor is known as the material supply center.

(8) The depot location of each material can be different from each other.

(9) The materials are loaded from the ground floor and moved to subsequent stories by the lift(s) and the lift returns to the ground floor after unloading. Every trip just involves moving one type of material.

(10) The candidate locations for lift installation can vary in their horizontal distances to the material depot (supply point) and the material delivery locations (demand point).

(11) Materials are horizontally transported by laborers. It therefore includes additional transportation costs to the costs of the project.

(12) Some demand points may not have access to certain lift installation candidate locations during one or more stages.

(13) The daily number of activities assigned for each lift shall not be more than the daily working hours of the workshop.

(14) These minimum working days are calculated depending on factors that may affect the construction, like the speed of manpower and other equipment available at the site (except the lift) before the optimization process. The maximum number of working days is based on some pre-determined work contract. The number of working days needed to meet the demand for materials must fall between these two.

(15) Lifts may not deliver the required materials on time. To reduce the possibility of delays, the suggested model's objective function includes a delay penalty in the form of working days.

Figure 1 illustrates the flowchart of the proposed model.

According to Figure 1, the candidate locations for lift installation are selected in consultation with site engineers and the project manager. Additionally, the material storage locations, technical specifications of the lifts (such as cabin dimensions and movement speed) and associated costs – including installation, dismantling, rental and operational costs – are predetermined. The contractual agreement and project timeline constraints determine the allowed time to complete the lifting operations. The loading and unloading time and quantity of required materials for each floor are also considered as input data, which are provided by the site engineers. Subsequently, the horizontal and vertical transportation times for materials are calculated, considering the lifts' movement speed, the workforce, the height of the floors and the horizontal distances involved. The model tries to determine the optimal number and

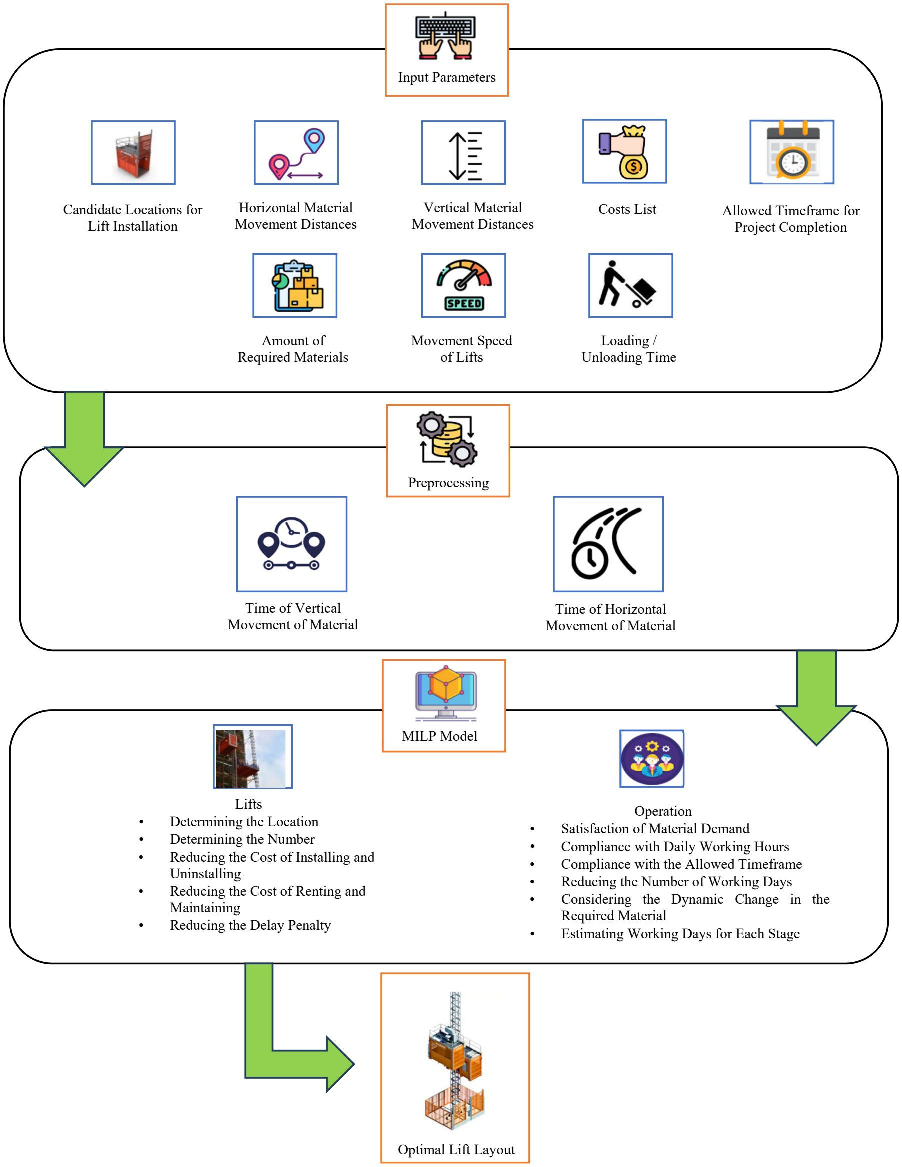

Figure 1. Flowchart of the proposed model. Source: Authors' own work

locations of the lifts in a site by using the aforementioned data. Moreover, the developed model can consider the various stages of construction (including lift relocation) and determine the optimum number of working days for each construction stage.

In the following text, the symbols and parameters of the model will be introduced in Table 2.

Table 2. Notations descriptions

Index Sets	Description
J	Set of all demand points for material delivery (index j)
S	Set of all construction stages (index s)
L	Set of all candidate locations for installing lifts based on expert assessment (index l)
K	Set of all available lift types (index k)
M	Set of all required material (index m)
Parameters	
d_{jms}	The amount of type m materials needed in unit j during construction stage s
$\overline{C}_k^{Install}$	The installation cost of the type k lift
$\overline{C}_k^{Uninstall}$	The uninstallation cost of type k lift
cap_{mkl}	Lifting capacity of type k lift installed at candidate installation location l to transfer type m material
$\overline{C}_k^{Rental}$	Rental cost of type k lift
$\overline{C}^{Delay}$	Daily project delay penalty
$\overline{C}_{lj}^{Horizontal}$	Horizontal transportation cost of materials from candidate installation location l to demand point j (per kilogram)
$\overline{C}_k^{Operation}$	Working cost of type k lift
ND_s^{Max}	The maximum number of working days for the construction stage s
ND_s^{Min}	The minimum number of working days for the construction stage s
T_m^{Load}	Loading/unloading time of type m material (per kilogram)
T_{mk}^{Load}	Loading/unloading time of type m material by type k lift
$T_{jkl}^{Transportation}$	Vertical transportation time of type k lift installed at candidate location l from the ground floor to demand point j
O_1, O_2	Large numerical constant
$T^{Working}$	Permissible daily working time of each lift
H^{Load}	Height level of material loading point
H_j	Demand point j height level
ACC_{jls}	The binary parameter that is equal to 1 if candidate point l has access to demand point j in the construction stage s, and otherwise equal to 0
V_k	The movement speed of movement of type k lift
Variables	
λ_{kls}	Auxiliary variable for calculating the installation cost of type k lift at candidate location l in the construction stage s
$\overline{\lambda}_{kls}$	Auxiliary variable for calculating the uninstallation cost of type k lift at candidate location l in the construction stage s
ND_s	The number of working days of the construction stage s
x_{jmkls}	The amount of type m materials that the type k lift installed at the candidate point l in the construction stage s delivers to demand point j
A_{kls}	Linearization variable
n_{jmkls}	The number of trips of type k lift installed at candidate point l to demand point j for supplying type m material in construction stage s
y_{kls}	The binary variable is equal to 1 if the type k lift is installed in the construction stage s in the candidate location l and is equal to 0 otherwise
$C^{Uninstall}$	The total uninstallation cost of lifts
$C^{Install}$	The total installation cost of lifts
C^{Rental}	The total rental cost of lifts
$C^{Horizontal}$	The total horizontal transportation cost of materials
C^{Delay}	The total penalty cost for project delays
$C^{Operation}$	The total operation cost of lifts
$T_{kls}^{Operation}$	The total vertical transportation time of type k lift installed at candidate location l in construction stage s
T_{kls}	The total working time of type k lift installed at candidate location l in construction stage s

Source(s): Authors' own work

3.1 Optimization model

The constraints of the proposed model are as follows:

$$\sum_{k\in K}\sum_{l\in L} x_{jmkls} = d_{jms} \qquad \forall j\in J, m\in M, s\in S \tag{1}$$

$$x_{jmkls} \le O_1 \times ACC_{jls} \qquad \forall j\in J, m\in M, k\in K, l\in L, s\in S \tag{2}$$

$$x_{jmkls} \le cap_{mkl} \times n_{jmkls} \qquad \forall j\in J, m\in M, k\in K, l\in L, s\in S \tag{3}$$

$$T_{kls}^{Operation} = 2\times\sum_{j\in J}\sum_{m\in M} n_{jmkls}\times T_{jkl}^{Transportation} \qquad \forall k\in K, l\in L, s\in S \tag{4}$$

$$T_{kls} = T_{kls}^{Operation} + 2\times\sum_{j\in J}\sum_{m\in M} n_{jmkls}\times T_{mk}^{Load} \qquad \forall k\in K, l\in L, s\in S \tag{5}$$

$$ND_s \times T^{Working} \ge T_{kls} \qquad \forall k\in K, l\in L, s\in S \tag{6}$$

$$ND_s \ge ND_s^{Min} \qquad \forall s\in S \tag{7}$$

$$ND_s \le ND_s^{Max} \qquad \forall s\in S \tag{8}$$

$$y_{kls}\times O_1 \ge x_{jmkls} \qquad \forall j\in J, m\in M, k\in K, l\in L, s\in S \tag{9}$$

$$\sum_{k\in K} y_{kls} \le 1 \qquad \forall l\in L, s\in S \tag{10}$$

$$\lambda_{kls} \ge y_{kls} - y_{kl(s-1)} \qquad \forall k\in K, l\in L, s\in\{s|s\ge 2, s\in S\} \tag{11}$$

$$\overline{\lambda}_{kls} \ge y_{kl(s-1)} - y_{kls} \tag{12}$$

The quantity of required materials at each demand point can be estimated before construction starts. Constraint (1) ensures that all the required materials for the project in each stage (d_{jms}) are appropriately met. Workers then unload materials from the lift and move them to the desired demand points. The internal architectural design of the building, for example, or the implementation of internal and external construction walls that obstruct some building units from others on certain floors may cause the demand points to become partly inaccessible for the lift(s) during project execution. In other words, some demand points may have no access to all the installed lift(s) on the site. Constraint (2) ensures the availability of demand points assigned to each lift. This can also ensure that all the demand points have at least one lift available during the execution of the project.

Due to capacity constraints, the lift(s) should move between floors several times. Therefore, constraint (3) calculates the number of transfers (n_{jmkls}) by considering the capacity of the lift(s) denoted as (cap_{mkl}). The volume and weight capacity of each lift are included. The minimum of them is considered as the effective lift capacity. Hence, the term (cap_{mkl}) in constraint (3) can guarantee the satisfaction of both volumes and weight capacities. In addition, Eq. (13) uses the formula below to find, the time it takes for each material to move, where the movement distance is divided by the lift speed, (V_k), therefore can capture the time it takes to move materials from one floor to another by the use of the lift(s) for the model accordingly.

$$T_{jkl}^{Transportation} = 2 \times \left(H_j - H^{Load}\right) \Big/ V_k \qquad \forall j \in J, k \in K, l \in L \tag{13}$$

Constraint (4) calculates the total relocation time for each lift at each stage, including the time needed to complete all assigned material transfers. Note that during the loading and unloading of materials between floors, a considerable amount of time is spent. Constraint (5) computes the total activity time of each lift (T_{kls}) at each work stage that involves these loading and unloading activities.

Assuming that the lift(s) moves only one type of material during each trip, the loading/unloading time of type *m* material by type *k* lift is calculated based on Eq. (14).

$$T_{mk}^{Load} = T_m^{Load} \times Cap_k \qquad \forall m \in M, k \in K \tag{14}$$

Construction tasks must be carried out within the permitted daily working hours. Constraint (6) denotes the number of working days at each stage (ND_s), determined based on authorized daily working hours, ($T^{Working}$). This constraint allows a project to remain on schedule and aligns with logical, established work time regulations.

The minimum required working days for project completion, (ND_s^{Min}), are predefined as a parameter before the optimization process begins. This is due to the main influential factors such as workforce speed and other installed equipment on the site apart from the lifts. Completion of the required material demands by the use of lift(s) before this minimum deadline, (ND_s^{Min}), cannot reduce the number of working days and the associated costs. That is, constraint (7) calculates how many and what kind of lift(s) are needed based on the other factors that affect the construction speed.

For no delay in lift(s) deliveries, a project may be completed within a minimum number of days, which is (ND_s^{Min}). However, completion of the project within this minimum number of days, (ND_s^{Min}), may raise the cost related to the usage of lift(s). The minimum number of working days required for the completion of the project is pre-calculated, which is called (ND_s^{Min}), before the start of the optimization process. This optimization considers major factors like the labor rate and all other equipment available on site except for the lifts. In exchange for this compromise, Constraint (8), allows the project completion date to be delayed to favor better cost optimization. The objective function (Eq. 22) incorporates a component $\left(C^{Delay}\right)$ to calculate the additional costs incurred for each day that the material delivery is delayed. By taking this approach, the overall project costs will be minimized as it finds a balance between the cost of using lifts and possible delays in material delivery. Constraint (8) also allows an upper limit for the number of working days, denoted as (ND_s), to ensure that project completion time remains reasonable despite delays.

Constraint (9) determines the type and position of the lift(s) used at each stage. Within this constraint, a sufficiently large number value for O_1 needs to be taken into account. On the other hand, this value cannot be chosen too large due to the reduction in computational complexity as well as the solution time of the model. An appropriate value for O_1 may be computed using Eq. (15).

$$O_1 \geq d_{jms} + 1 \tag{15}$$

Constraint (10) in the model will ensure that no more than one lift is installed at each location. This prevents the situation where more than one lift could be installed at a demand point. Installation and uninstallation of lifts are defined by Constraints (11) and (12), respectively. These constraints specify the associated cost and logistics for deploying the lifts across all stages of construction. Precisely, the binary variable $\left(\lambda_{kls}\right)$ is utilized to determine whether a lift is installed in the current construction stage. If there is an installed lift in the current stage but not in the prior stage, the value of $\left(\lambda_{kls}\right)$ will be marked as 1; otherwise, it is marked as 0. Then, the binary variable $(\overline{\lambda}_{kls})$ represents the cost of removing lift(s) in each stage. It will cover the costs and logistics of moving or uninstalling the lifts during the construction project.

3.2 Objective function

The optimization model presented here will provide the optimum number and locations of lift (s) to be deployed for the project. This is because of minimizing the overall cost of the lift(s), including:

(1) Installation and dismantling costs

(2) Rental costs

(3) Operational costs (e.g. energy consumption, maintenance)

(4) Costs related to the horizontal movement of materials.

On the other hand, an additional penalty term has been added to the objective function to prevent any delay in material delivery. In this way, the optimization process will be motivated to find the solution that reduces the possible delay in material delivery. The objective function of the proposed model has been defined in Eq. (15). In this regard, the complete objective function can determine the optimal deployment plan of lifts, which creates a good balance between material delivery on time and at low costs, since it considers all components of cost, including delays.

$$z = min\, C^{Install} + C^{Uninstall} + C^{Rental} + C^{Operation} + C^{Horizontal} + C^{Delay} \tag{16}$$

$$C^{Install} = \sum_{k\in K}\sum_{l\in L}\overline{C}_k^{Install} \times y_{kls(s=1)} + \sum_{k\in K}\sum_{l\in L}\sum_{s=2}^{n(S)}\overline{C}_k^{Install} \times \lambda_{kls} \tag{17}$$

$$C^{Uninstall} = \sum_{k\in K}\sum_{l\in L}\sum_{s=2}^{n(S)}\overline{C}_k^{Uninstall} \times \overline{\lambda}_{kls} + \sum_{k\in K}\sum_{l\in L}\overline{C}_k^{Uninstall} \times y_{kl(n(S))} \tag{18}$$

$$C^{Rental} = \sum_{k\in K}\sum_{l\in L}\sum_{s\in S} ND_s \times y_{kls} \times \overline{C}_k^{Rental} \tag{19}$$

$$C^{Operation} = \sum_{k\in K}\sum_{l\in L}\sum_{s\in S}\overline{C}_k^{Operation} \times \mathrm{T}_{kls}^{Operation} \tag{20}$$

$$C^{Horizontal} = \sum_{j\in J}\sum_{m\in M}\sum_{k\in K}\sum_{l\in L}\sum_{s\in S} x_{jmkls} \times \overline{C}_{lj}^{Horizontal} \tag{21}$$

$$C^{Delay} = \sum_{s\in S}\left(ND_s - ND_s^{Min}\right) \times \overline{C}^{Delay} \tag{22}$$

During the development of the construction project, the quantity and type of required materials may change. Consequently, the specific needs concerning the type and location of the lift(s) will shift with time. On account of a possible change of requirements, costs related to the installation and uninstallation processes of the lift(s), $(C^{Install})$ and $(C^{Uninstall})$, respectively, are concerned with the proposed objective function, Eq. (16). The goal of this methodology is to avoid unnecessary increases in project costs that would result from the reconfiguration of the lift system. Installation costs $(C^{Install})$ and cost of dismantling $(C^{Uninstall})$ are determined respectively from Eq. (17) and Eq. (18).

In the objective function, the terms (C^{Rental}), $(C^{Operation})$ and (C^{Delay}) represent the rental cost of the lift(s) installed on-site, the operational cost of the lift(s) and the costs incurred due to delays in completing the project, respectively; calculated by Eqs (19), (20) and (22), respectively. The optimum number of working days, type and number of lift(s) are resulted by these equations, correspondingly.

The objective function involves an element, $(C^{Horizontal})$, which accounts for the cost of laborers moving materials horizontally on various floors. This cost element is expressed by Eq. (21). Since this cost element can drive the optimization to minimize the distance and effort required to horizontally transport materials, the model can optimize the locations of lift(s) to decrease the need for long horizontal material movement, leading to cost savings and better efficiency.

3.3 Linearization of the proposed model

More and wider varieties of solvers are available for precisely solving linear models compared with nonlinear models. So, this paper has linearized nonlinear constraints without using any approximations to allow the use of a wide variety of precise solvers for solving the proposed model. This approach reinforces computational efficiency and also may provide many more accurate degrees in the solution process. More specifically, Eq. (19) used for calculating the rental cost of the lift(s), (C^{Rental}), is of a non-linear form. This constraint has been restructured in a linear form as provided in Eq. (23), to reduce the corresponding computational burden and solution time.

$$C^{Rental} = \sum_{k\in K}\sum_{l\in L}\sum_{s\in S} A_{kls} \times \overline{C}_k^{Rental} \qquad \forall\, k \in K, l \in L, s \in S \tag{23}$$

The value of (A_{kls}) must equal the result of $(ND_s \times y_{kls})$ to equalize Eq. (23) with Eq. (19). The equivalence of these two values is ensured by Eq. (24) to Eq. (26).

$$A_{kls} \le ND_s \qquad \forall\, k \in K, l \in L, s \in S \tag{24}$$

$$A_{kls} \le O_2 \times y_{kls} \qquad \forall\, k \in K, l \in L, s \in S \tag{25}$$

$$A_{kls} \ge ND_s - O_2(1 - y_{kls}) \qquad \forall\, k \in K, l \in L, s \in S \tag{26}$$

To reduce the volume of calculations, Eq. (27) is proposed to calculate the numerical constant O_2.

$$O_2 = ND_s^{Max} + 1 \tag{27}$$

4. Case study

The “Koohe noor” residential, office and commercial complex in Mashhad, Iran, has been selected as a case study for the optimization model. Figure 2 shows a view of the case study.

This project consists of 32 floors, and floors 5+ to 25+ are simulated in the optimization model. The plan of the project varies on each floor. One of the interesting features of the case study is how from the 6th to the 14th floor, the building is split into two independent, disconnected sections. At least one lift will be installed in each section to have access to all demand points. According to Figures 2 and 3, there are five delivery locations (demand points) for connected floors and four delivery locations (demand points) for separate floors. In Figures 2 and 3, the candidate locations for lift installation are also indicated. These locations were chosen in consultation with engineers and the project manager. The locations of the material depot (supply points) placed on the ground floor are also indicated in Figures 3 and 4.

Figure 2. Case study. Source: Authors' own work

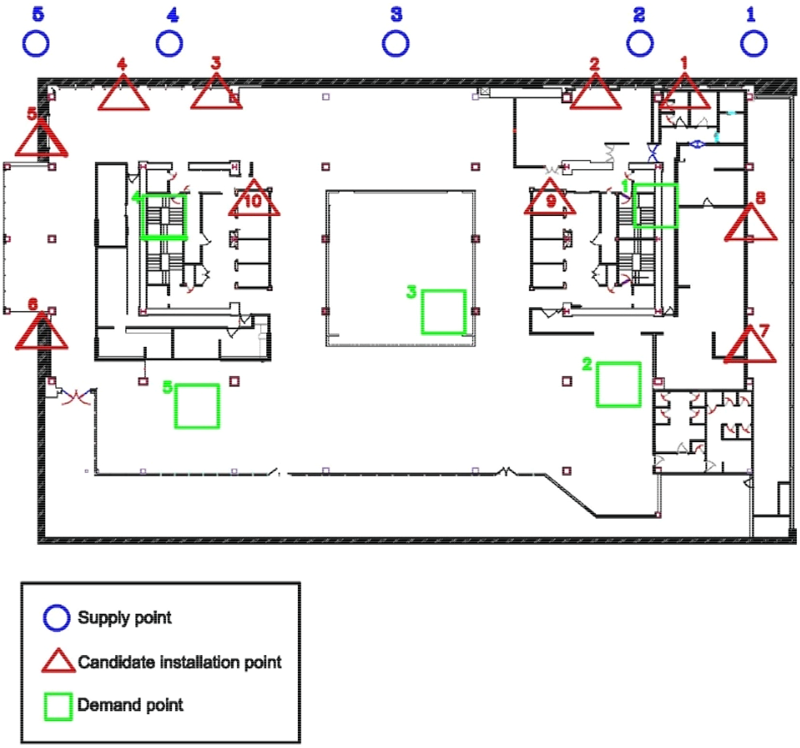

Figure 3. Depot locations and delivery of materials and candidate locations for lift installation in connected floors. Source: Authors' own work

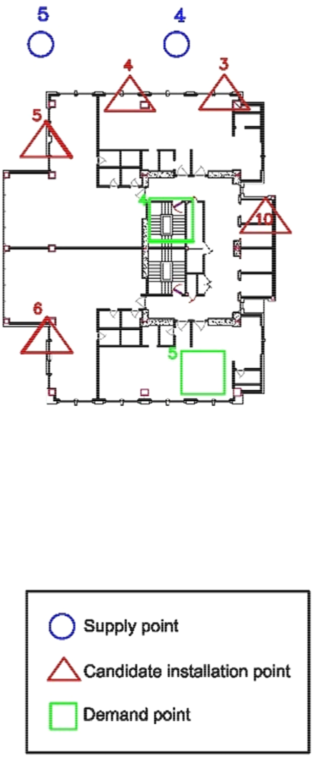

Figure 4. Depot locations and delivery of materials and candidate locations for lift installation on separated floors. Source: Authors' own work

In this project, an unlimited number of five types of lifts can be rented. Table 3 provides the key specifications and cost parameters (in Euro) for these lift options. Furthermore, the cost of installing and dismantling the lifts is estimated at 1800 Euros.

According to the amount of required materials, the equipment available on-site and the manpower employed, the whole construction process is divided into three stages. The allowed time range for the completion of the project and the limit of the allowed working hours in each stage are reported in Table 4. The daily delay penalty is considered equal to 300 Euros.

It is assumed that a lift is used to transport five types of required materials. For instance, the required materials for the fifth floor in Stage 1 are shown in the following Table 5. The workers

Table 3. Technical specifications of lifts

Lift type	Capacity (ton)	Cabin dimensions (m)	Velocity (m/min)	Rental cost (per day)	Operational cost (per Hour)
1	2	3*3*1.4	36	121.8	5.04
2	1.5	3*3.2*1.4	33	96.2	4.90
3	1	3*2.8*1.5	35	76.9	4.32
4	2	3*2.1*1.4	34	104.8	5.40
5	1	3*2.1*1.4	30	60.9	4.61

Source(s): Authors' own work

Table 4. The allowed time range for the completion of the project

Stage	Minimum allowed working days	Maximum allowed working days	Daily working hours of lifts
1	400	800	8
2	300	600	8
3	250	500	8

Source(s): Authors' own work

Table 5. The required materials for the 5th floor in Stage 1

	Demand point 1	Demand point 2	Demand point 3	Demand point 4	Demand point 5
Martial *A*	35.8	33.7	65.5	33.0	21.8
Martial *B*	21.9	20.6	40.1	20.2	13.3
Martial *C*	36.7	34.5	67.1	33.8	22.3
Martial *D*	244.8	230.4	447.3	225.6	148.8
Martial *E*	244.8	230.4	447.3	225.6	148.8

Source(s): Authors' own work

on the floors will transport the materials horizontally. Every ton of material transported for one meter is estimated to cost 1 cent.

Also, the loading/unloading time for each type of needed material is represented in Table 6.

5. Numerical results

The proposed model is implemented in IBM® ILOG CPLEX 12.10 package and solved using the OPL interface in a machine with Windows® 10, 32 GB RAM and Core i7 CPU. In the following, the proposed model is solved using a case study and the results are shown. Different scenarios have also been tested and examined to determine how factors would influence the optimal layout of lifts. The mathematical model for obtaining the optimum lift layout has been developed and is available at https://github.com/smartconstructiongroup/Lift-Layout-Planning for those interested in adopting new cases.

5.1 Optimal layout

Figure 5 illustrates the optimal layout for stages 1, 2 and 3 including the number, location and type of lifts as determined by the proposed method.

Thus, the proposed method chooses locations 2, 3, 7 and 9 at stage 1, locations 2, 3 and 7 at stage 2 and locations 1, 2, 3, 7 and 9 at stage 3 for lift installations. As can be seen in Figure 5, the proposed model assigns type 4 lifts to location 2 and type 5 lifts at other locations. This building has two separate parts on some floors (Figures 2 and 4), as mentioned earlier. In the

Table 6. Loading/unloading time of each type of material

	Martial *A*	Martial *B*	Martial *C*	Martial *D*	Martial *E*
Loading / Unloading Time (Per Kilogram)	1	1.2	1	0.67	0.86

Source(s): Authors' own work

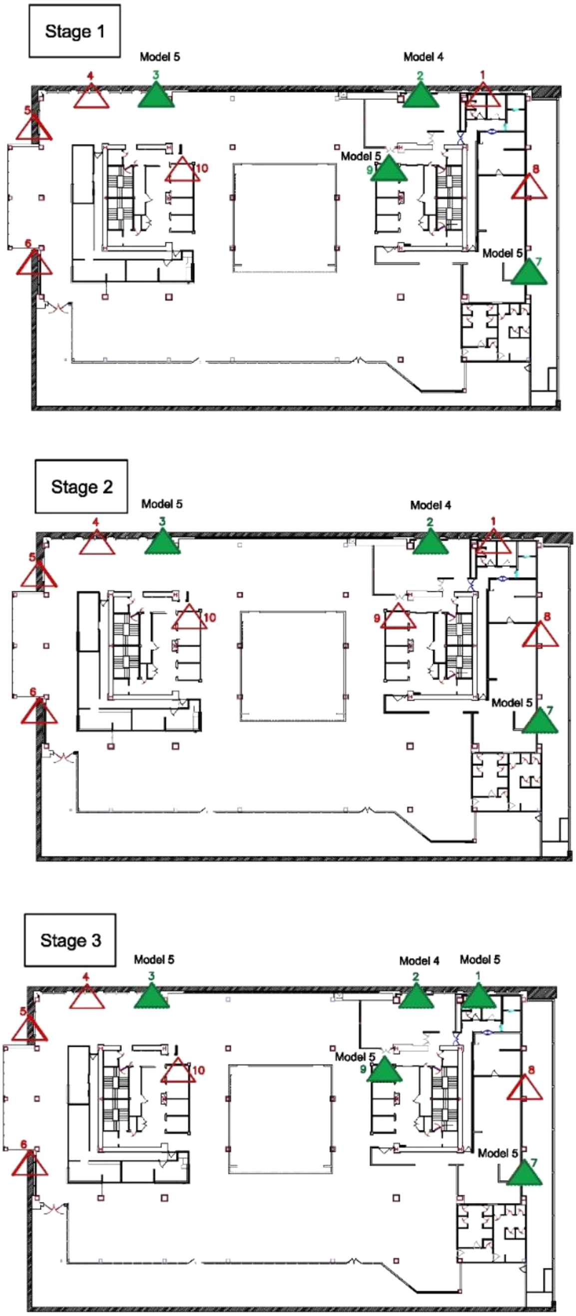

Figure 5. Optimal layout of lifts. Source: Authors' own work

optimal solution, each section is installed with at least one lift at each stage to ensure that all the demand points reach the lift. The total optimal layout cost comes out to be 356, 960 Euros.

Figure 6 presents the cost distribution: rental cost 274,960 Euros, installation cost 10,800 Euros, dismantling cost 10,800 Euros, operating cost 31,760 Euros and horizontal material movement cost 23,520 Euros. Stage 1 lasts 413 days with a 13-day delay, Stage 2 lasts 302 days with a 2-day delay and Stage 3 spans lasts 252 days with a 2-day delay. As a result, the total lift delay is 17 working days, with a penalty of 5,100 Euros.

5.2 Construction stages

In the optimization model, lifts at various stages of construction are laid out at the same time to avoid useless changes during the project's implementation. The optimum solution (Figure 5) requires a single uninstall and reinstall throughout the project. In Stage 2, the lift at location 9 is dismantled and then installed again in Stage 3 because of reduced material requirements. This operation costs 3,600 Euros against a rental cost of roughly 18,400 Euros for Stage 2. The model would, therefore, select the dismantling of the lift in the second stage. Generally, this will be a rise of about 3.7% in project costs if the lifts' arrangement in the second stage is the same as in the first stage. In the third stage, two more lifts will be added at locations 9 and 1 due to the increase in material delivery demand. If a similar lift layout to the first stage is assumed in the third stage, the number of working days increases by 6.2%, and the project costs by 4.3% compared to the optimal solution.

In this example, with the same layout for lifts in the third stage of construction as in the second stage, working days increased by 16.1% and project costs by 11.9% over the optimum layout. From the analysis, it's clear that construction speed and the different stage requirements can influence how lifts are arranged. However, the useless change of lift configuration increases the cost of installation and dismantling. So, the proposed method finds all stages' layouts simultaneously. Figure 7 shows the importance of that. In the case of the layout shown in Figure 7, the model proposed is solved independently for each stage. In this Figure, the lift installed at location 2 in Stage 1 and the installed lift at location 9 in Stage 2 are of type 4, while all other lifts are of type 5. In this case, the installation and dismantling costs of lifts become inefficient. Thus, changes in lift type and location during project implementation increase in comparison with the optimum layout (Figure 5). This scheme, which considers every single stage individually to decide on the optimum layout, has resulted in a 3.7% higher cost compared with the optimal one (Figure 7). Thus, taking installation and dismantling costs into consideration and finding the layout for all construction stages at the same time has reduced the overall project cost. Hence, the proposed method may better manage the costs arising from changes in the layout of lifts compared to the approaches available in the literature review (Table 1).

5.3 Horizontal movement of materials by workers

Supply and demand points are situated at various distances from the potential sites of installation. Locations chosen by the model would result in optimized horizontal material movement when the cost of horizontal material movement is integrated into the objective

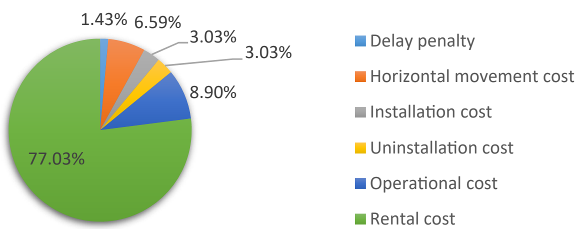

Figure 6. Pie chart of share of different expenses. Source: Authors' own work

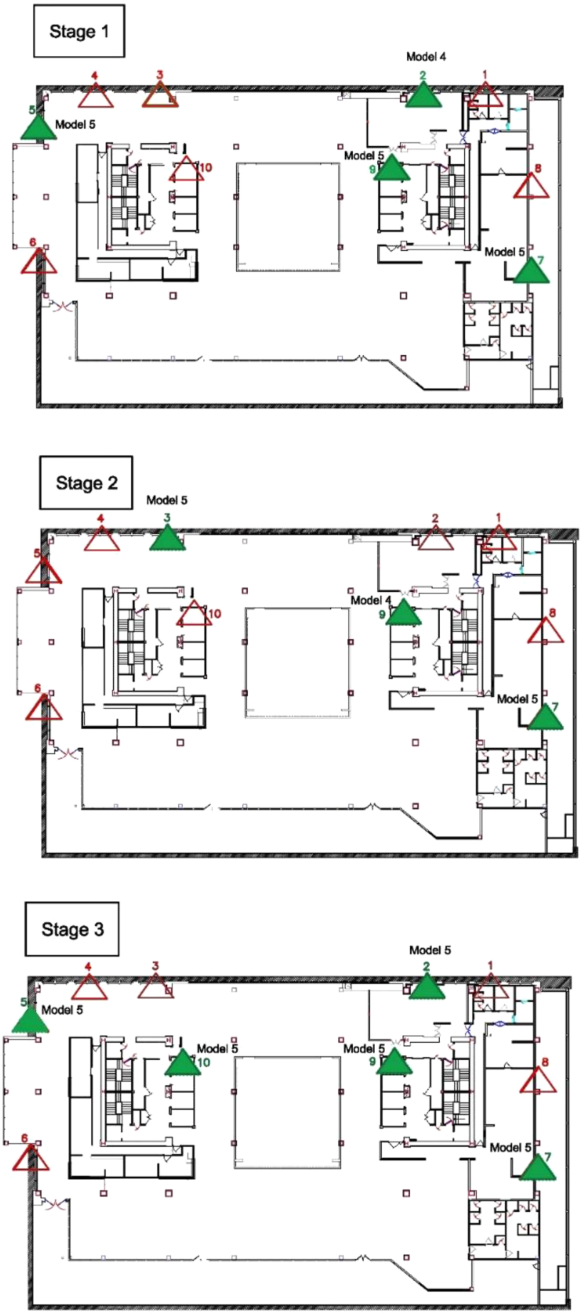

Figure 7. Making separate decisions about each construction stage. Source: Authors' own work

function. If this cost is neglected, the candidate locations become similar to each other. In reality, all these solutions are different from each other on the grounds of horizontal displacement. Table 7 compares some of these solutions with the optimal solution (Figure 5) concerning horizontal movement and total project costs. These results reveal that neglect of horizontal movement cost increases horizontal displacement by 68.7% and overall project costs by 4.5% compared to the optimum layout. As a result, horizontal transportation for workers in the layout obtained from the proposed method may be easier and more efficient compared to methods that ignore this (such as Hwang (2009), Ruokokoski and Siikonen (2017), Kim *et al*. (2020) and Yun *et al*. (2021)).

5.4 Timely completion of the project

Some important characteristics of the proposed method include timely project completion and minimization of delays caused by material delivery through lifts. The minimum number of working days estimated in the case study, based on the available facilities and manpower, was found to be 950 days. In the optimal layout (Figure 5), only 17 days (1.8%) of delay occurred due to lift performance. To mitigate this minor delay, Improving the number or type of lifts (as shown in Table 8) would be necessary, leading to at least a 3.7% increase in project costs. For this reason, the proposed method allows this delay to avoid increasing costs in the optimal layout.

The delay penalty in the objective function is the essential driving force for minimizing delays due to material delivery by lifts. Without having the delay penalty in the objective function, the number of lifts installed decreases, as depicted in Table 9. In practice, this means an increase of 1,078 days or 211% in the number of working days and a rise in project costs by 81% compared with the optimum layout. The delay penalty in the objective function, therefore, has to play an important role in timely completion, thereby reducing the costs of the projects. Among the methods reviewed in the literature review (Table 1), only Huang and Wang (Huang and Wong, 2019) considers delay penalty. Therefore, the proposed method may better manage the delay in material delivery and the resulting costs compared to other methods in the literature.

Table 7. Impact of horizontal movement on lift layout and costs

		Stage 1	Stage 2	Stage 3	Horizontal displacement Cost	Gap (%)	Total project costs Cost	Gap (%)
1	Location	2,3,7,9	3,7,9	1,2,3,7,9	31,780	35.12	363,960	1.96
	Type	5,5,5,4	5,5,4	5,5,5,5,4				
2	Location	3,7,9,10	3,7,9	1,3,7,9,10	32,160	36.73	365,420	2.37
	Type	5,5,4,5	5,5,4	5,5,5,4,5				
3	Location	6,7,9,10	6,7,9	1,6,7,9,10	39,680	68.70	372,940	4.47
	Type	4,5,5,5	4,5,5	4,5,5,5,5				

Source(s): Authors' own work

Table 8. Layout without delay

Stage	Installation location	Lift type	Working days	Total working days	Total costs
1	2,3,7,9	5,2,5,4	400	950	370,100
2	5,7,9	3,5,4	300		
3	1,5,7,9,10	5,3,5,4,5	250		

Source(s): Authors' own work

Table 9. Layout caused by the removal of the delay penalty

Stage	Installation location	Lift type	Working days	Total working days	Total costs
1	7,10	5,5	885	2,045	646,320
2	7,10	5,5	495		
3	7,10	5,5	665		

Source(s): Authors' own work

5.5 The rental cost of lifts

Within the optimal layout, the rent of lifts accounts for 77% of the total project cost. By removing this cost from the objective function, the layout found is shown in Table 10. This layout considers the improvements in lift type and number to reduce extra spending. However, these adjustments increase overall costs by 78% when implemented. The type and the number of lifts should, therefore, be selected considering the rental cost. Most of the methods in the literature (Table 1) ignored this cost. Therefore, the proposed method may provide a more cost-effective layout in practice.

5.6 Type and number of lifts

The type and number of lifts are treated as decision variables in the proposed model. Tables 11 and 12, which are prepared to study the importance of this issue, have been considered in this

Table 10. Layout caused by the removal of the rental cost

Stage	Installation location	Lift type	Working days	Total working days	Total costs
1	2,4,7,9,10	1,1,1,1,1	400	950	635,620
2	2,4,7,9,10	1,1,1,1,1	300		
3	2,4,7,9,10	1,1,1,1,1	250		

Source(s): Authors' own work

Table 11. Layout of lifts if their number is predetermined

Lifts number	Stage	Locations	Type	Working days	Total working days	Total costs
2	1	7,10	4,4	712	1,652	606,500
	2	7,10	4,4	401		
	3	7,10	4,4	539		
3	1	2,3,7	4,5,5	540	1,248	436,540
	2	2,3,7	4,5,5	302		
	3	2,3,7	4,5,5	406		
4	1	2,3,7,9	5,5,5,5	443	1,076	373,440
	2	2,3,7,9	5,5,5,5	300		
	3	2,3,7,9	5,5,5,5	333		
5	1	2,3,7,9,10	5,5,5,5,5	400	966	376,820
	2	2,3,7,9,10	5,5,5,5,5	300		
	3	2,3,7,9,10	5,5,5,5,5	266		
6	1	1,2,3,7,9,10	5,5,5,5,5,5	400	950	428,700
	2	1,2,3,7,9,10	5,5,5,5,5,5	300		
	3	1,2,3,7,9,10	5,5,5,5,5,5	250		

Source(s): Authors' own work

Table 12. Layout of lifts if their type is predetermined

Lifts type	Stage	Locations	Working days	Total working days	Total costs
1	1	3,7,9	471	1,039	492,440
	2	3,7,9	300		
	3	1,3,7,9	268		
2	1	1,5,7,9	400	989	427,640
	2	5,7,9	300		
	3	2,5,7,9	289		
3	1	1,4,7,9	427	1,003	393,000
	2	4,7,9	319		
	3	1,4,7,9,10	257		
4	1	1,4,7,9	400	970	440,000
	2	4,7,9	300		
	3	1,4,7,9	270		
5	1	1,5,7,9	443	1,039	357,780
	2	5,7,9	330		
	3	1,5,7,9,10	266		

Source(s): Authors' own work

regard. It is assumed in Table 11 that the number of lifts is fixed for all stages while the lift type is still considered a decision variable. The results obtained are presented as follows:

(1) If the number of lifts is set to 2, working days will increase by 70.8% and project costs by 69.9% compared to optimal layout.

(2) If three lifts are used, working days will increase by 29.1% and project costs will increase by 22.3%.

(3) If four lifts are used, the working days and project costs will increase by 11.3% and 4.7%, respectively, compared to the optimal solution.

(4) Utilizing five lifts does not alter the number of working days compared to the optimal layout; however, it results in a 5.6% increase in project costs.

(5) Employing six lifts results in a 1.8% reduction in working days compared to the optimal solution; however, it concurrently leads to a 20.1% increase in project costs.

The above findings indicate that optimally determining the required number of lifts significantly impacts the number of working days and the overall project costs.

Table 12 assumes that the type of lifts is fixed across all stages, while the number of lifts remains a decision variable. The results are as follows:

(1) If only type 1 lift is used, working days and project costs will increase by 7.4% and 38%, respectively.

(2) If only type 2 lift is used, working days and project costs will increase by 2.3% and 19.8%, respectively.

(3) If only type 3 lift is used, working days and project costs will increase by 3.7% and 10.1%, respectively.

(4) If only a type 4 lift is used, working days will not increase much. However, project costs will increase by 23.3%.

(5) If only a type 5 lift is used, the project costs will not increase much. However, working days will increase by 7.4%.

The above shows that the lift type is an important factor in reducing the number of working days and project costs. The methods Matsuzaki *et al*. (1999), Abdelhafiez *et al*. (2007), Fang *et al*. (Fung *et al*., 2008), Huang *et al*. (2010) and Huang and Wang (Huang and Wong, 2019) in the literature review (Table 1) consider the type of lift as predetermined. Therefore, the proposed method may have better performance than them in practice.

The results from Tables 11 and 12 demonstrate that both the type and number of lifts installed on-site significantly impact their efficiency. Consequently, the proposed method simultaneously determines the optimal type and number of lifts.

5.7 Performance analysis of the proposed method on different case studies

This paper attempted to examine the performance of the proposed method with a real-world case study. Also, in order to gain further evidence, the performance of the model was also tested on two alternative scenarios:

(1) If the minimum allowed working days for stages 1, 2 and 3 decrease to 300, 220 and 190 days, 6, 5 and 7 lifts are installed in these stages, respectively to complete the project without delays.

(2) If the minimum allowed working days for stages 1, 2 and 3 decrease to 200, 150 and 120 days, by installing 9, 7 and 10 lifts in these stages the required material is provided with a 27 days delay at stage 3.

Construction rate, which depends on the number of workers and equipment on the site, is one of the most influential factors among the various case studies. In Table 13, the performance of the proposed method is demonstrated in two more scenarios, considering an increased construction rate compared to the initial case study.

As shown in Table 13, the proposed method completed the project within the allocated time by increasing the number of lifts. Therefore, the proposed method can demonstrate adaptability across different case studies, managing costs and potential delays by making optimum decisions based on the available manpower and equipment at the site.

Table 13. Layout in case of daily required material increase

		Stage 1	Stage 2	Stage 3	Total cost
Case Study	Minimum Allowed Working Days	400	300	250	356,960
	Location	2,3,7,9	2,3,7	1,2,3,7,9	
	Type	4,5,5,5	4,5,5	5,4,5,5,5	
	Optimal Working Days	412	301	251	
Scenario 1	Minimum Allowed Working Days	300	220	190	348,706
	Location	1,2,4,5,7,8	1,2,4,7,8	1,2,4,5,7,8,10	
	Type	5,5,5,5,5	5,5,5,5	5,5,5,5,5	
	Optimal Working Days	300	220	190	
Scenario 2	Minimum Allowed Working Days	200	150	120	364,151
	Location	1,2,3,4,5,6,7,8,10	1,2,3,4,5,7,8	1,2,3,4,5,6,7,8,9,10	
	Type	5,5,5,5,5,5,5,5,5	5,5,5,5,5,5,5	5,5,5,5,5,5,5,5,5,5	
	Optimal Working Days	200	150	147	

Source(s): Authors' own work

5.8 Input data sensitivity analysis

One of the key factors influencing the performance and accuracy of any optimization model is the proper selection of its input parameters. To assess the sensitivity of the proposed method to these parameters, a sensitivity analysis is conducted on the input parameters.

For this purpose, Tables 14–19 have been prepared. In these tables, the initial layout refers to the optimal layout shown in Figure 5. In Tables 14–19, changes are applied to the parameters of the case study. The layout obtained from these changes is referred to as the modified layout. In Tables 14–19, the cost of the modified layout is calculated based on the initial parameters (the actual parameters of the case study). Finally, the gap between the cost of the initial layout and the cost of the modified layout is reported to determine the sensitivity of the proposed method to changes in the parameters.

To investigate the sensitivity of the proposed method to the demand for construction materials, a sensitivity analysis was conducted, the results of which are summarized in Table 14. For this purpose, the parameters related to material demand were gradually varied from 5% to 30%.

As it can be perceived from Table 14, a 5% increase in material demand leads to a 3% rise in project costs. Furthermore, increases of 10%, 15%, 20% and 30% in material demand result in project cost escalations of 10%, 16%, 17% and 20%, respectively. These findings indicate that the proposed method is highly sensitive to the material demand parameter. Consequently, accurate estimation of this parameter is crucial for determining the optimal layout.

The sensitivity of the proposed method to the cost of lift rental is examined in Table 15. For this analysis, the lift rental costs were gradually increased from 15% to 100%.

As illustrated in Table 15, an increase in rental costs of up to 15% does not result in any change in project costs. Even a 100% increase in rental costs leads to only a 4% difference in overall project costs. This indicates that the proposed method exhibits low sensitivity to the accuracy of lift rental cost estimates.

Table 16 examines the sensitivity of the proposed method to lift operational costs. For this purpose, the operational costs were gradually increased from 50% to 200%. The findings presented in Table 16 reveal that even with a 200% increase in operational costs, the optimal layout remains unchanged. Therefore, the proposed method demonstrates low dependency on the accuracy of this parameter.

Table 14. Dependency of the proposed method on required material

Material changes	Stage	Lift type	Lift number	Cost Modified layout	Initial layout	Gap
5%	1	5	5	375,172	386,922	
	2	5	4			3%
	3	5	5			
10%	1	5	5	380,844	417,874	10%
	2	5	4			
	3	5	6			
15%	1	5	5	387,852	448,850	16%
	2	5	4			
	3	5	6			
20%	1	5	5	409,395	479,828	17%
	2	5	4			
	3	5	6			
30%	1	5	6	448,738	541,876	20%
	2	5	5			
	3	5	7			

Source(s): Authors' own work

Table 15. Dependency of the proposed method on lift rental costs

Rental cost changes	Stage	Lift type	Lift number	Cost Modified layout	Initial layout	Gap
15%	1	4	1	386,293	386,293	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			
20%	1	5	4	406,726	410,813	1%
	2	5	3			
	3	5	5			
30%	1	5	4	431,606	438,233	1.5%
	2	5	3			
	3	5	5			
40%	1	5	4	456,506	465,653	2%
	2	5	3			
	3	5	5			
50%	1	5	4	481,386	493,092	2.4%
	2	5	3			
	3	5	5			
75%	1	5	4	543,586	561,612	3.3%
	2	5	3			
	3	5	5			
100%	1	5	4	605,806	630,132	4%
	2	5	3			
	3	5	5			

Source(s): Authors' own work

Table 16. Dependency of the proposed method on lift operational cost

Operational cost changes	Stage	Lift type	Lift number	Cost Modified layout	Initial layout	Gap
50%	1	4	1	371,779	371,779	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			
100%	1	4	1	387,605	387,605	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			
200%	1	4	1	419,232	419,232	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			

Source(s): Authors' own work

Table 17. Dependency of the proposed method on horizontal material transport costs

Horizontal material transport cost changes	Stage	Lift type	Lift number	Cost Modified layout	Initial layout	Gap
50%	1	4	1	367,867	367,867	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			
100%	1	5	4	378,962	379,662	0.2%
	2	5	3			
	3	5	5			
200%	1	5	4	400,802	402,781	0.5%
	2	5	4			
	3	5	5			
300%	1	5	4	422,934	425,885	0.7%
	2	5	4			
	3	5	5			

Source(s): Authors' own work

Table 18. Dependency of the proposed method on installation costs

Installation cost changes	Stage	Lift type	Lift number	Cost Modified layout	Initial layout	Gap
50%	1	5	4	366,749	366,749	0%
	2	5	3			
	3	5	5			
100%	1	5	4	375,338	377,549	0.6%
	2	5	4			
	3	5	5			
200%	1	5	4	393,258	399,149	1.5%
	2	5	4			
	3	5	5			
300%	1	5	4	412,009	420,750	2.1%
	2	5	4			
	3	5	5			

Source(s): Authors' own work

Table 17 investigates the sensitivity of the proposed method to horizontal material transportation costs. For this analysis, the horizontal transportation costs were gradually varied from 50% to 300%.

As shown in Table 17, a 50% increase in horizontal transportation costs does not alter the layout of the lifts. Even with a 300% increase in horizontal material transportation costs, the project costs rise by only 0.7%. This indicates that the proposed method exhibits low sensitivity to this parameter.

Table 18 examines the sensitivity of the proposed method to the costs of lift installation and uninstallation. For this purpose, the installation and uninstallation costs were gradually varied from 50% to 300%.

As demonstrated in Table 18, a 50% increase in installation and uninstallation costs does not result in any changes to the lift layout. Even with a 300% increase in these costs, the project

Table 19. Dependency of the proposed method on delay penalty

Delay penalty changes	Stage	Lift type	Lift number	Cost Modified layout	Initial layout	Gap
100%	1	4	1	360,254	360,254	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			
200%	1	4	1	364,421	364,421	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			
300%	1	4	1	368,664	368,664	0%
		5	3			
	2	4	1			
		5	2			
	3	4	1			
		5	4			

Source(s): Authors' own work

costs rise by only 2.1%. This shows that the proposed method is not highly sensitive to this parameter.

Table 19 investigates the sensitivity of the proposed method to delay penalties. For this analysis, the delay penalties were gradually increased from 50% to 300%.

As shown in Table 19, even with a 300% increase in delay penalties, the costs associated with the lift layout remain unchanged. This indicates that the proposed method exhibits very low sensitivity to this parameter.

6. Discussion

As explained in the previous section, the proposed method was tested and validated using a real-world case study. The proposed method can optimally determine the number, type and installation location of the required lifts for the project.

The quantity and type of required materials during project execution may vary. If these changes are significant, they may necessitate alterations in the lift layout. The proposed method addresses this by dividing the entire construction process into distinct stages based on changing requirements. It then determines the optimal layout for each stage by considering the varying material demands at different construction stages, as well as the costs related to lift installation and uninstallation. The findings of this study reveal that ignoring installation and uninstallation costs in the case study led to a 3.7% increase in project costs. In contrast, previous methods (Table 1) did not account for construction phases when determining the lift layout. Therefore, the proposed method can provide a more economical layout by simultaneously optimizing the construction stages.

Reducing delays in material delivery is another innovation of the proposed method. To address this aim, delays in material delivery were incorporated as penalties in the objective function. This approach effectively managed material delivery delays in the case study, resulting in only 17 days of delay in a 950-day project. The results show that neglecting delay penalties in the case study would lead to a 211% increase in working days and an 81% rise in project costs. Most previous methods (Table 1) overlooked the costs associated with material delivery delays. Consequently, the proposed method may outperform previous approaches in managing both costs and working days.

To facilitate horizontal material movement carried out by workers on each building floor, horizontal movement costs are included in the objective function. The findings of this paper show that ignoring these costs could lead to approximately a 70% increase in horizontal movements and a 4.5% increase in project costs in the case study. Therefore, the proposed method can better facilitate horizontal movements on different floors compared to some previous methods (Table 1).

Most of the previous methods (Table 1) did not consider the rental cost of the lift. The results of this paper show that ignoring the rental cost of the lift can lead to a 78% increase in costs in the case study. Hence, the proposed method incorporates daily lift rental costs in the objective function to prevent the project cost from increasing.

The results of this paper show that if the type and number of lifts are predetermined, the labor costs and the number of working days can increase significantly. For this reason, the proposed method considers the type and number of required lifts as decision variables.

In the results section, the sensitivity of the proposed method to input parameters was examined. The findings indicate that the proposed method is highly sensitive to the amount of required materials. While showing less sensitivity to parameters such as rental cost, installation and uninstallation costs, operational cost, horizontal material movement cost and delay penalties. Therefore, the accurate estimation of required materials is crucial for the performance of the proposed method.

7. Conclusion and future research directions

According to the literature review, the optimal layout of the construction lifts, including the determination of the type, number and installation location, has not been explored yet. To bridge this gap, in this paper, a MILP model is proposed for the optimum layout of building lifts. The results proved the efficiency of the proposed model while determining the contribution of each effective factor. First of all, the project is divided into different stages based on the material requirement and construction rate. Then, by taking into consideration installation and dismantling costs, rental costs and operational costs, the type and number of lifts are determined. Based on this, materials delivery delays can be reduced to the minimum amount based on the type and number of lift optimization. In this regard, installation locations are also optimized to reduce horizontal material flow and transportation by workers and laborers. This model was tested and analyzed using one real case study. The results confirmed the favorable performance of the proposed method.

Like other existing methods in the literature, the proposed method is prone to a few limitations. This limitation indeed opens avenues for further research and development in this area. The following suggestions are made for improvement in future studies:

(1) In the proposed method, the locations of supply points are predetermined. Future research can further facilitate the horizontal displacement process by considering the location of the supply points as a decision variable.

(2) The effectiveness of the proposed method heavily depends on the accuracy of estimating the required materials of the project. However, precise estimation at the early stages of a project can be challenging. To address this issue, using stochastic mathematical models and fuzzy methods may prove beneficial.

(3) The proposed method divides the project into stages based on the requirements changes. Optimizing this segmentation can significantly enhance the performance of the proposed method. Therefore, future research can focus on the optimal project phasing based on the requirements changes and integrate it with the proposed method.

(4) In the proposed method, the ground floor is selected as the material depot location. However, in practical scenarios, other floors may also serve this purpose. Extending the current method to incorporate such considerations would improve its alignment with real-world conditions.

(5) The construction lift layout problem is recognized as an NP-hard problem. Therefore, solving this problem at a large scale can be challenging. In this regard, employing heuristic approaches with acceptable accuracy can facilitate the decision-making process.

(6) In addition, future research can focus on safety constraints such as worker safety, preventing equipment component interference and ergonomic factors, to enhance the practical applicability of the proposed method.

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