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GENETIC ALGORITHM-BASED TEMPORARY ELEVATOR PLANNING FROM A SPATIO-TEMPORAL PERSPECTIVE

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Abstract

For temporary elevator planning, optimization with meta-heuristic algorithms is an effective approach. Existing temporary elevator planning is rarely conducted from a spatio-temporal perspective. This research proposes a spatio-temporal planning model with a genetic algorithm to address this deficiency. The experiment test results show that the total cost of the optimized solution is reduced by 37.48% compared to the initial solution. The proposed model solves the limitation that the service day and floor of temporary elevators are planned separately, which, when considered simultaneously, help reduce the cost of temporary elevators.

Introduction

With the increase in the construction of high-rise projects, the vertical transportation of resources is becoming significant (Wu et al., 2020). The temporary elevator is a piece of equipment that mainly transports workers and small to medium-sized materials (Shin et al., 2011; Park et al., 2013). Temporary elevator planning plays an important role in transportation capacity and cost (Cho et al., 2011; Cho et al., 2013). Effective temporary elevator planning is what the project team cares about, and it is a critical element for the successful completion of high-rise projects (Kim et al., 2016; Jalali Yazdi et al., 2018).

Temporary elevator planning is a complex dynamic process. The transportation demand for temporary elevators, i.e., the quantity of resources transported on each floor each day, varies frequently and significantly (Wu and García de Soto, 2021). To this effect, temporary elevator planning should be adjusted accordingly to meet actual transportation demands. In other words, the number and type of temporary elevators serving different days and floors should be dynamic and not static, which is in line with the requirements of spatio-temporal construction management (Ardila and Francis, 2020).

Informal traditional temporary elevator planning mainly relies on experience and knowledge from similar projects (Hwang, 2009); therefore, some heuristic and statistical methods are proposed for selecting temporary elevators (Shin et al., 2011). For example, one heuristic method depends on the transportation frequencies of projects and temporary elevators (Shin et al., 2011). Another statistical method is based on the height, area, floor number, and construction duration of projects (Ye et al., 2016). These methods are easy to use but not guaranteed to be accurate enough because different planning solutions cannot be compared carefully (Shin et al., 2011). To make temporary elevator planning more effective, some transportation time models are established using discrete-event simulation, and three types of time in one transportation, i.e., cab motion time, cab door operation time, and resource transfer time, are considered (Shin et al., 2011; Park et al., 2013; Jung et al., 2017).

Temporary elevators are classified according to specifications such as lifting height, loading capacity, and rated speed. Finding an optimal temporary elevator combination by trial and error is difficult or even impossible when candidates increase explosively (Shin et al., 2011). This problem is equally prominent in the zoning operation of temporary elevators (Park et al., 2013). To tackle such cases, meta-heuristic algorithms like genetic algorithms (GA) have been employed in various temporary elevator planning for single or multiple objectives. For instance, an equipment selection model incorporating GA is built to minimize the cost of temporary elevators (Shin et al., 2011), a zoning operation model combining GA is created to reduce transportation time (Park et al., 2013), and a zoning operation-based equipment selection model applying GA is developed to solve the time-cost-environment tradeoff (Koo et al., 2016).

However, existing temporary elevator planning is rarely conducted from a spatio-temporal perspective. To be specific, although the service floor of temporary elevators has been taken into account, the service day of temporary elevators is scarcely involved. Thus, the installation and dismantlement dates of temporary elevators cannot be determined reasonably when there are multiple ones in a project. Moreover, temporary elevator planning loses an opportunity to be further optimized.

Based on the above considerations, this research investigates how to configure temporary elevators to serve specific days and floors to satisfy transportation demands, and GA, a typical meta-heuristic algorithm, is used for optimization. The rest of this paper is structured as follows. First, the modeling of temporary elevator spatio-temporal planning is elaborated. Next, an experimental test is executed to verify the proposed model. Finally, conclusions and outlook are provided.

Spatio-Temporal planning modeling

This section presents the spatio-temporal planning modeling of temporary elevators, and the objective and optimization of the model are described in detail.

Model objective

The objective of the model is to minimize the total cost of configured temporary elevators while satisfying the limit of transportation time, and it is expressed in Equations (1) to (3). C^T indicates the total cost of temporary elevators, consisting of fixed and variable costs. C_e^F indicates the fixed cost (e.g., installation cost, dismantlement cost) of temporary elevator e. C_e^V indicates the variable cost (e.g., rental cost, maintenance cost, personnel cost) of temporary elevator e per day. N_e^D indicates the service day number of temporary elevator e. T_d^D indicates the transportation time on day d, which is determined by the maximum transportation time among all temporary elevators. $T_{e,d}^E$ indicates the transportation time of temporary elevator e on day d. T_d^L indicates the transportation time limit on day d, which is determined by the project team.

$$\min C^T = \sum_{e=1}^{E}(C_e^F + C_e^V \cdot N_e^D) \quad (1)$$

$$T_d^D = \max\{T_{1,d}^E, T_{2,d}^E, \dots, T_{e,d}^E\} \quad \forall d \in D \quad (2)$$

$$T_d^D \leq T_d^L \quad \forall d \in D \quad (3)$$

The model focuses on the transportation of workers during the morning peak time for the following reason. On a given day, the transportation of workers is basically concentrated during the morning, noon, and afternoon peak times, while that of materials is mainly concentrated in the morning and afternoon, and sometimes in the evening. Among these time periods, the transportation of workers during the morning peak time is recognized as the most critical because transportation demands are the most concentrated in this time period, and its delay has the greatest impact on construction productivity.

To avoid confusing transportation, the following three transportation rules are implemented: 1) if the number of floors to be served is more than that of available temporary elevator cabs on a given day, then a floor is only served by one temporary elevator cab; 2) if the number of floors to be served is equal to that of available temporary elevator cabs on a given day, then a floor is only served by one temporary elevator cab, and a temporary elevator cab only serves one floor; and 3) if the number of floors to be served is less than that of available temporary elevator cabs on a given day, then a temporary elevator cab only serves one floor.

The transportation time of one task is divided into three parts: 1) the cab motion time of the temporary elevator, 2) the cab door operation time of the temporary elevator, and 3) the transfer time of transported workers, as expressed in Equation (4). $T_{d,t,e}$ indicates the transportation time of task t served by temporary elevator e on day d. $N_{d,t}^S + 1$ indicates that the number of segments in task t on day d plus the process back to the ground. $T_{d,t,e,s}^M$ indicates the cab motion time of temporary elevator e in segment s of task t on day d. $T_{d,t,e}^O$ and $T_{d,t,e}^C$ indicate the cab door opening and closing times of temporary elevator e in task t on day d, respectively. $N_{d,t}^W$ indicates the number of transported workers in task t on day d. $T_{d,t}^B$ and $T_{d,t}^L$ indicate the boarding and leaving times of transported workers in task t on day d, respectively. For $T_{d,t,e,s}^M$, if the distance of segment s is not less than the distance required for the cab of temporary elevator e to perform a complete acceleration and deceleration process, it is determined by the first fraction of Equation (5), otherwise by the second fraction of that Equation. $D_{d,t,s}^M$ indicates the distance of segment s in task t on day d. V_e^R, V_e^A, and V_e^D indicate the cab rated speed, acceleration, and deceleration of temporary elevator e, respectively.

$$T_{d,t,e} = \sum_{s=1}^{N_{d,t}^S+1} T_{d,t,e,s}^M + \left(N_{d,t}^S + 1\right) \cdot \left(T_{d,t,e}^O + T_{d,t,e}^C\right) + N_{d,t}^W \cdot \left(T_{d,t}^B + T_{d,t}^L\right) \quad (4)$$

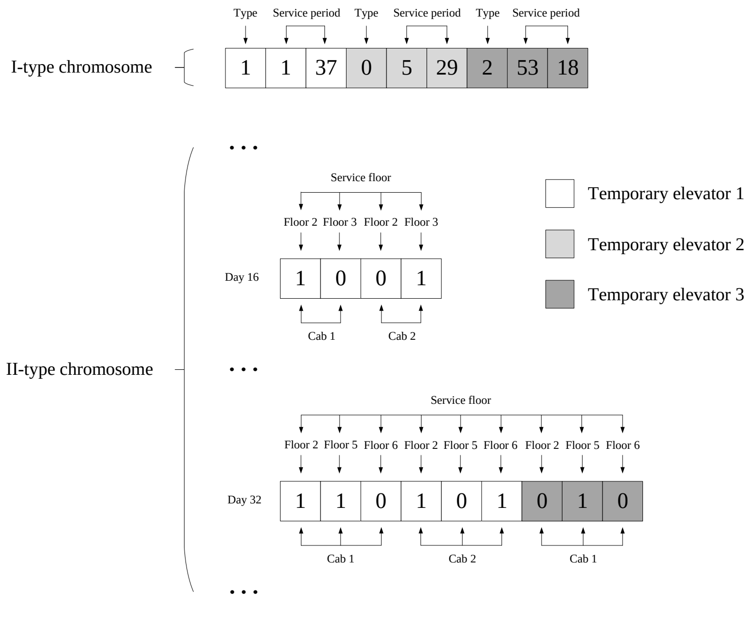

Figure 1: I-type and II-type chromosomes

$$T^M_{d,t,e,s} = \begin{cases} \frac{V_e^R}{V_e^A} + \frac{V_e^R}{V_e^D} + \frac{D^S_{d,t,s} - \frac{{V_e^R}^2}{2V_e^A} - \frac{{V_e^R}^2}{2V_e^D}}{V_e^R}, D^S_{d,t,s} \geq \frac{{V_e^R}^2(V_e^A + V_e^D)}{2V_e^A V_e^D} \\ \sqrt{\frac{2D^S_{d,t,s}}{\begin{vmatrix} {V_e^A}^2 & -{V_e^D}^2 \\ V_e^A & V_e^D \end{vmatrix}}}(V_e^A + V_e^D), D^S_{d,t,s} < \frac{{V_e^R}^2(V_e^A + V_e^D)}{2V_e^A V_e^D} \end{cases} \quad (5)$$

Model optimization

The I-type and II-type chromosomes, as illustrated in Figure 1, are designed to facilitate the model optimization.

In the I-type chromosome, the information for each temporary elevator consists of two parts with three genes, and they are encoded in real numbers. The first part with one gene represents the type of temporary elevators, numbered according to specifications such as lifting height, loading capacity, and rated speed. If the number is zero, like in the case of temporary elevator 2 in Figure 1, it means that there is no temporary elevator, and the service period in the I-type chromosome is ignored although it is displayed; meanwhile, the service floors on each day in the II-type chromosome are excluded. The second part with two genes represents the start and end days of the service period of temporary elevators. The gene with a smaller number represents the start day, and if the two genes are equal, there is only one day in the service period. As shown in Figure 1, the service period of temporary elevator 1 is from days 1 to 37, and that of temporary elevator 3 is from days 18 to 53. It should be noted that the number of temporary elevators is not fixed in the I-type chromosome and can be expanded as needed.

In the II-type chromosome, the information for available temporary elevators consists of the genes representing the service floors on each day, and they are encoded in binary. If the configuration of a temporary elevator is a dual cab, like in the case of temporary elevator 1 in Figure 1, the service floor of each cab is represented respectively. The gene with "1" represents that the service floor of the cab includes the corresponding floor, otherwise does not. As shown in Figure 1, on day 32, the service floor of cab 1 of temporary elevator 1 includes floors 2 and 5, that of cab 2 of temporary elevator 1 includes floors 2 and 6, and that of cab 1 of temporary elevator 3 includes floor 5.

The I-type and II-type criteria are formulated below to exclude inherently infeasible I-type and II-type chromosomes, respectively.

The I-type criteria are comprised of seven items:

- The first item is that there is at least one available temporary elevator. As shown in Figure 2 (a), the types of all temporary elevators are zero. In this case, there is no available temporary elevator, so the chromosome is infeasible.
- The second item is that a service day is covered by at least one available temporary elevator. As shown in Figure 2 (b), the service period of temporary elevator 1 is from days 37 to 50, and that of temporary elevator 3 is from days 1 to 28. In this case, days 29 to 36 cannot be covered, so the chromosome is infeasible.

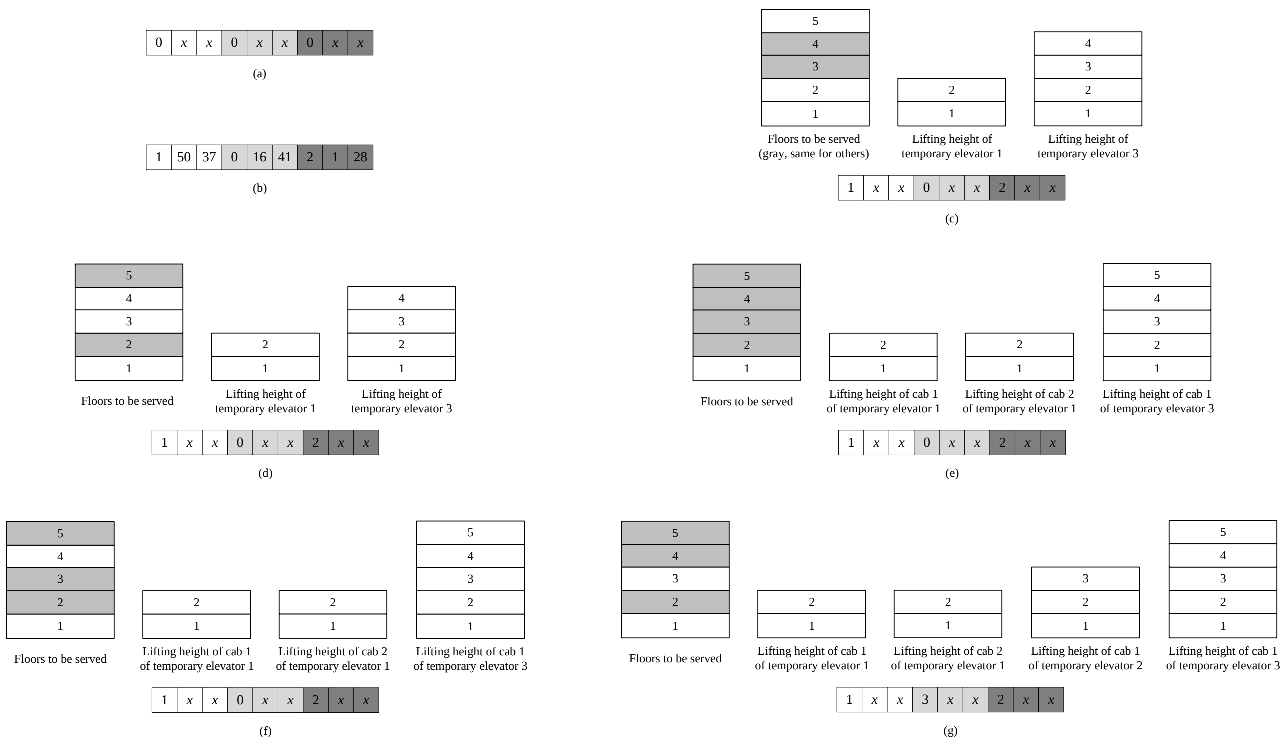

Figure 2: Examples of inherently infeasible I-type chromosomes

- The third item is that the lifting height of any available temporary elevators is not lower than the height of at least one floor to be served on each day. As shown in Figure 2 (c), there are floors 3 and 4 to be served on a given day, and the lifting heights of temporary elevators 1 and 3 can reach up to floors 2 and 4, respectively. In this case, temporary elevator 1 cannot reach up to the floors to be served, so the chromosome is infeasible.
- The fourth item is that the height of any of the floors to be served is not higher than the lifting height of at least one available temporary elevator on each day. As shown in Figure 2 (d), floors 2 and 5 are to be served on a given day, and the lifting heights of temporary elevators 1 and 3 can reach up to floors 2 and 4, respectively. In this case, floor 5 cannot be reached, so the chromosome is infeasible.
- The fifth item, following the aforementioned first transportation rule, is that the number that the height of all floors to be served is not higher than that of a specific floor to be served is not less than the number that the lifting height of available temporary elevator cabs is not higher than that of this specific floor on a given day. As shown in Figure 2 (e), there are four floors to be served and three available temporary elevator cabs on a given day; the number that the floors to be served is not higher than floor 2 is one, and the number that the lifting height of available temporary elevator cabs is not higher than floor 2 is two. In this case, cabs 1 and 2 of temporary elevator 1 only serve floor 2, so the chromosome is infeasible.
- The sixth item, following the aforementioned second transportation rule, is that the number that the height of all floors to be served is not higher than the height of a specific floor to be served is not less than the number that the lifting height of available temporary elevator cabs is not higher than the height of this specific floor, and the number that the height of all floors to be served is not lower than the height of a specific floor to be served is not more than the number that the lifting height of available temporary elevator cabs is not lower than the height of this specific floor, on a given day. As shown in Figure 2 (f), there are three floors to be served and three available temporary elevator cabs on a given day; the number that the floors to be served is not lower than floor 3 is two, and the number that the lifting height of available temporary elevator cabs is not lower than floor 3 is one. In this case, floors 3 and 5 are only served by cab 1 of temporary elevator 3, so the chromosome is infeasible.
- The seventh item, following the aforementioned third transportation rule, is that the number that the height of all floors to be served is not lower than the height of a specific floor to be served is not more than the number that the lifting height of available temporary elevator cabs is not lower than the height of this specific floor on a given day. As shown in Figure 2 (g), there are three floors to be served and four available temporary elevator cabs on a given day; the number that the floors to be served is not lower than floor 4 is two, and the number that the lifting height of available temporary elevator cabs is not lower than floor 4 is one. In this case, floors 4 and 5 are only served by cab 1 of temporary elevator 3, so the chromosome is infeasible.

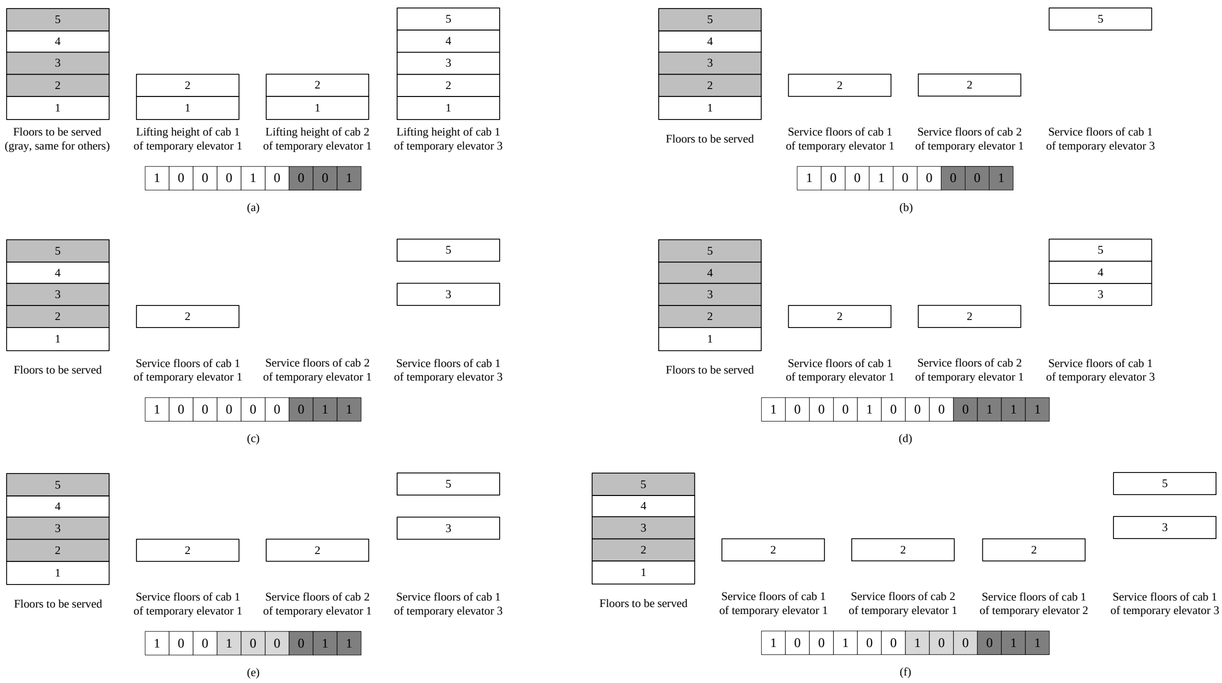

Figure 3: Examples of inherently infeasible II-type chromosomes

The II-type criteria are comprised of six items:

- The first item is that the lifting height of a temporary elevator cab is not lower than the height of the floor it serves. As shown in Figure 3 (a), the lifting height of cab 2 of temporary elevator 1 reaches up to floor 2, and it serves floor 3. In this case, floor 3 cannot be served by cab 2 of temporary elevator 1, so the chromosome is infeasible.
- The second item is that a floor to be served is covered by at least one temporary elevator cab. As shown in Figure 3 (b), floor 2 is served by cabs 1 and 2 of temporary elevator 1, and floor 5 is served by cab 1 of temporary elevator 3. In this case, floor 3 does not be served, so the chromosome is infeasible.
- The third item is that an available temporary elevator cab serves at least one floor to be served. As shown in Figure 3 (c), cab 1 of temporary elevator 1 serves floor 2, and cab 1 of temporary elevator 3 serves floors 3 and 5. In this case, cab 2 of temporary elevator 1 does not serve floors, so the chromosome is infeasible.
- The fourth item, following the aforementioned first transportation rule, is that a floor is only served by one temporary elevator cab. As shown in Figure 3 (d), there are four floors to be served and three available temporary elevator cabs on a given day, and floor 2 is served by cabs 1 and 2 of temporary elevator 1. In this case, floor 2 is not only served by one temporary elevator cab, so the chromosome is infeasible.
- The fifth item, following the aforementioned second transportation rule, is that a floor is only served by one temporary elevator cab and a temporary elevator cab only serves one floor. As shown in Figure 3 (e), there are three floors to be served and three available temporary elevator cabs on a given day, floor 2 is served by cabs 1 and 2 of temporary elevator 1, and cab 1 of temporary elevator 3 serves floors 3 and 5. In this case, floor 2 is not only served by one temporary elevator cab, and cab 1 of temporary elevator 3 does not only serve one floor, so the chromosome is infeasible.
- The sixth item, following the aforementioned third transportation rule, is that a temporary elevator cab only serves one floor. As shown in Figure 3 (f), there are three floors to be served and four available temporary elevator cabs on a given day, and cab 1 of temporary elevator 3 serves floors 3 and 5. In this case, cab 1 of temporary elevator 3 does not only serve one floor, so the chromosome is infeasible.

The GA-based model optimization process with 12 steps is listed below, and its flow chart is shown in Figure 4.

- Step 1: Set the model optimization parameters, including the population size S^P, the crossover probability P^C, the mutation probability P^M, and the generation number N^G.
- Step 2: Generate inherently feasible initial I-type chromosomes with the population size S^P randomly.
- Step 3: According to each I-type chromosome, generate inherently feasible initial II-type chromosomes with the population size S^P randomly.
- Step 4: Evaluate the fitness of each II-type chromosome (i.e., transportation time), and infeasible II-type chromosomes are penalized by setting a worse fitness (i.e., more transportation time).
- Step 5: Select II-type chromosomes according to the roulette wheel rule, and the II-type chromosome with less transportation time has the more probability of being selected.
- Step 6: According to the crossover probability P^C and the mutation probability P^M, conduct the crossover and mutation operations to the selected II-type chromosomes, and evaluate their fitness like Step 4.
- Step 7: If the generation number N^G of II-type chromosomes is reached, go to Step 8; otherwise, go to Step 5.
- Step 8: Evaluate the fitness of each I-type chromosome (i.e., total cost), and infeasible I-type chromosomes are penalized by setting a worse fitness (i.e., more total cost).
- Step 9: Select I-type chromosomes according to the roulette wheel rule, and the I-type chromosome with less total cost has the more probability of being selected.

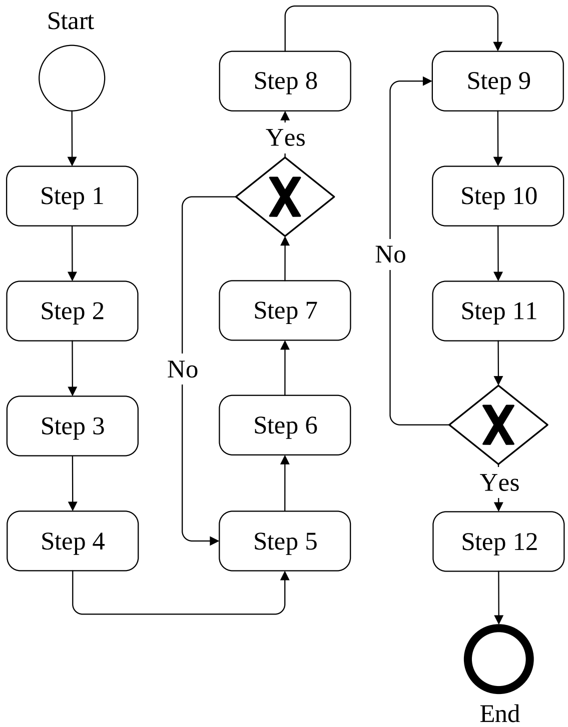

Figure 4: Flow chart of the GA-based model optimization process

Table 1: Specifications and costs of two types of temporary elevators

Type	Cab number	Loading capacity (kg)	Lifting height (m)	Rated speed (m/min)	Acceleration (m/s²)	Deceleration (m/s²)	Fixed cost (CNY*)	Variable cost (CNY*/d)
1	2	2,000	250	63	0.21	0.35	38,500.00	1,301.67
2	2	2,000	200	36	0.12	0.20	26,400.00	751.67

* 1 CNY ≈ 0.16 USD

- Step 10: According to the crossover probability P^C and the mutation probability P^M, conduct the crossover and mutation operations to the selected I-type chromosomes, and evaluate their fitness like Steps 3 to 8.
- Step 11: If the generation number N^G of I-type chromosomes is reached, go to Step 12; otherwise, go to Step 9.
- Step 12: Output the optimal I-type and II-type chromosomes.

Experimental test

A 36-story high-rise project with a construction duration of 411 days is used for testing the proposed model. The specifications and costs of the two types of temporary elevators are summarized in Table 1, which consists of cab number, lifting height, loading capacity, rated speed, acceleration, deceleration, fixed cost, and variable cost. The model optimization parameters are set as shown in Table 2.

Table 2: Model optimization parameters

Model optimization parameter	Value
Population size S^P	50
Crossover probability P^C	0.9
Mutation probability P^M	0.1
Generation number N^G	10

The details of the initial and optimized solutions for the service period of temporary elevators are listed in Table 3. In the initial solution, temporary elevator 1 with type 1 and temporary elevator 2 with type 2 serve all days. In the optimized solution, the construction duration can be divided into three stages according to the service periods of two temporary elevators. The first stage is from day 1 to day 332, and temporary elevator 1 with type 1 is available. The second stage is from day 333 to day 341, and temporary elevator 1 with type 1 and temporary elevator 2 with type 2 are available. The third stage is from day 342 to day 411, and temporary elevator 2 with type 2 is available.

The partial details of the initial and optimized solutions for the service floor of temporary elevators are listed in Table 4. On day 72, floors 6, 8, 11, and 12 need to be served. On day 339, floors 30, 31, and 36. On day 347, floors 29, 30, 34, and 35. In the initial solution, all cabs of temporary elevators 1 and 2 serve all the floors. In the optimized solution, on day 72, cab 1 of temporary elevator 1 serves floor 11, and cab 2 of temporary elevator 1 serves floors 6, 8, and 12; on day 339, cab 1 of temporary elevator 1 serves floor 36, cab 2 of temporary elevator 1

Table 3: Service period details of the initial and optimized solutions

Solution	Type	Start day	End day
Initial	1	1	411
	2	1	411
Optimized	1	1	341
	2	333	411

Table 4: Partial service floor details of the initial and optimized solutions

Solution	Day	Temporary elevator	Cab	Service floor
Initial	72	1	1	6, 8, 11, and 12
			2	6, 8, 11, and 12
		2	1	6, 8, 11, and 12
			2	6, 8, 11, and 12
	339	1	1	30, 31, and 36
			2	30, 31, and 36
		2	1	30, 31, and 36
			2	30, 31, and 36
	347	1	1	29, 30, 34, and 35
			2	29, 30, 34, and 35
		2	1	29, 30, 34, and 35
			2	29, 30, 34, and 35
Optimized	72	1	1	11
			2	6, 8, and 12
	339	1	1	36
			2	31
		2	1	31
			2	30
	347	2	1	29 and 35
			2	30 and 34

Table 5: Cost details of the initial and optimized solutions

Cost	Initial		Optimized		Reduction value (CNY)	Reduction rate
	Value (CNY)	Percentage	Value (CNY)	Percentage		
Fixed	64,900.00	7.14%	64,900.00	11.42%	-	-
Variable	843,922.74	92.86%	503,251.40	88.58%	-	-
Total	908,822.74	100.00%	568,151.40	100.00%	340,671.34	37.48%

serves floor 31, cab 1 of temporary elevator 2 serves floor 31, and cab 2 of temporary elevator 2 serves floor 30; and on day 347, cab 1 of temporary elevator 2 serves floors 29 and 35, and cab 2 of temporary elevator 2 serves floors 30 and 34.

The details of the initial and optimized solutions for the cost of temporary elevators are listed in Table 5. The fixed and variable costs of the initial solution are 64,900.00 CNY and 843,922.74 CNY, respectively, which account for 7.14% and 92.86% of the total cost of the initial solution (908,822.74 CNY). The fixed and variable costs of the optimized solution are 64,900.00 CNY and 503,251.40 CNY, respectively, which account for 11.42% and 88.58% of the total cost of the optimized solution (568,151.40 CNY). Compared to the initial solution, the total cost of the optimized solution is reduced by 340,671.34 CNY, which accounts for 37.48% of the initial solution.

The transportation time of the initial and optimized solutions on each day is shown in Figure 5. Their maximum transportation times are 27.68 min and 70.07 min on day 202 for the initial and optimized solutions, respectively, both less than the 90-minute transportation time limit. Compared to the initial solution, the temporary elevators in the optimized solution are more fully utilized within the transportation time limit.

Conclusions and outlook

Temporary elevator planning imposes a significant impact on the completion of high-rise projects. To enhance temporary elevator planning, this research proposes a spatio-temporal planning model with GA for minimizing the total cost of configured temporary elevators while satisfying the limit of transportation time. Because the transportation of workers during the morning peak time is the bottleneck of a day, it is selected as the concerned transportation object. For estimating the transportation time of one task, the cab motion time of the temporary elevator, the cab door operation time of the temporary elevator, and the transfer time of transported workers are taken into account. In order to facilitate optimization, two types of chromosomes are created. The I-type chromosome is used to express the number, type, and service period of temporary elevators, and the II-type chromosome is used to express the service floor of temporary elevators. In the meantime, the I-type and II-type criteria are formulated to exclude inherently infeasible two types of chromosomes. Moreover, in the

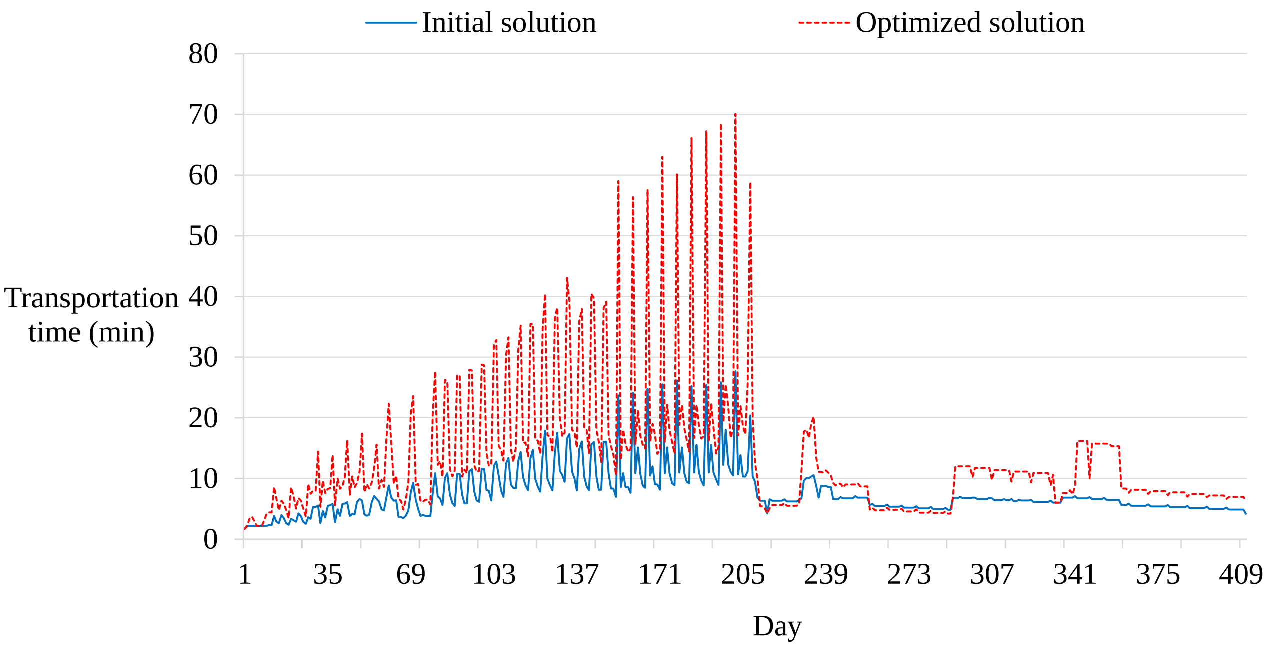

Figure 5: Transportation time of the initial and optimized solutions on each day

GA-based model optimization process, a two-level nested loop is specially designed for the two types of chromosomes. To demonstrate the proposed model, a high-rise project was tested. Compared to the initial solution, the total cost of the optimized solution is reduced by 37.48%, showing that the proposed model can effectively reduce the cost of temporary elevators.

In this research, multiple planning objects, including service days and floors, are integrated into one planning model, which solves the limitation that service days and floors are planned separately, resulting in a further reduction in the cost of temporary elevators. Meanwhile, when there exist multiple temporary elevators in a project, the installation and dismantlement dates of temporary elevators can be determined with evidence to support the decision-making process of the project team. Although the proposed model focuses on the transportation of workers during the morning peak time, it also applies to the transportation of other resources and periods. For example, if the project team is more concerned with the transportation of materials in the morning or afternoon, or the transportation of workers during the noon or afternoon peak time, it is only necessary to update parameters such as the transfer time of transported resources and the limit of transportation time accordingly.

The genetic algorithm adopted in the proposed planning model is a typical meta-heuristic algorithm. This category of algorithms can be applied to a wider range of models and used to solve large-scale models in a faster manner; nevertheless, it cannot guarantee the optimal solution of models, and it is difficult to precisely measure the accuracy of solutions. Mathematical programming is another category of the commonly used optimization method. Compared to the meta-heuristic algorithm that combines random and local search algorithms for optimization operations, mathematical programming describes optimization operations with mathematical equations that can be adjusted to provide solutions with quality assurance. However, it has special requirements for the characteristics and structure of models and is relatively inefficient in solving large-scale models. Ongoing work by the authors investigates the integration of mathematical programming into the spatio-temporal planning model of temporary elevators and compares the computational performance of mathematical programming versus meta-heuristic algorithms.

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