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ORIGINAL ARTICLE

GA optimization model for solving tower crane location problem in construction sites

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Abstract Tower crane is increasingly becoming one of the key components of temporary site layout facilities in most construction projects. Determining the location of tower crane is an essential task of layout planning, which is also the central focus of this study. The optimization of tower crane location depends on many interrelated factors, including site constraints, shape and size of the buildings, type and quantity of required materials, crane configurations, crane type, and construction site layout. These factors vary from one project to another, resulting to complicated site layout strategies and approaches. This fact makes the crane location problem impractical to be solved depending on experience of practitioners only which was gained by assuming and through trial and error.

This paper aimed at developing an optimization model to solve tower crane location problem in construction sites. The objective was to minimize the total transportation time. Genetic Algorithms (GA) optimization technique is utilized to solve the problem. A numerical example is presented to test and validate the results obtained by the model.

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1. Introduction

Tower crane is a basic machine for lifting and transporting material and devices. The construction process for buildings and many engineering fields requires transporting different materials and equipment in a short period, which creates the importance of tower crane presence in most construction sites. Selection of location for tower cranes to be used in constructing a building is among the most important issues in planning the construction operations.

Tower crane location must be selected to suit the requirements of the job. If the crane's basic characteristics do not match the job's requirements then it may lead to significant effects in terms of high cost, possible delays, and unsafe work

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Abbreviations

X_{si}, Y_{si}, Z_{si}	coordinates of supply points (m)
X_{dj}, Y_{dj}, Z_{dj}	coordinates of demand points (m)
X_c, Y_c	coordinates of tower crane (m)
L_{ij}	distance between supply (i) and demand (j) (m)
L_i	distance between crane point and supply point (m)
L_j	distance between crane point and demand point (m)
Z_{ij}	vertical distance between demand point and supply point (m)
θ_{ij}	angle between L_i and L_j (rad)
α	jib simultaneous movement parameter
β	hook simultaneous movement parameter
Q_{ij}	quantity of material to be handled from supply (i) to demand (j) (ton)
C_{ij}	capacity of tower crane for the cycle of loading between supply (i) and demand (j) (ton)
T_a	time for trolley radial movement (min)
T_w	time for trolley tangent movement (min)
V_a	radial velocity of trolley (m/min)
ω	slewing velocity of crane jib (r.p.m)
TL_{vij}	vertical hoisting time when the hook is loaded (min)
TU_{vij}	vertical hoisting time when the hook is unloaded (min)
V_{vl}	vertical hoisting velocity of loaded hook (m/min)
V_{vu}	vertical hoisting velocity of unloaded hook (m/min)
T_{ij}	cycle time between supply (i) and demand (j) (min)
L_{xc}, L_{yc}	dimensions of crane base area (m)
L_{xs}, L_{ys}	dimensions of supply area (m)
L_{xd}, L_{yd}	dimensions of demand area (m)

conditions. The use of any type of crane requires planning but tower cranes require more than usual because their structures, foundations, and presence on the site are generally for as long as the heavy construction phases continue. In selecting the most suitable location of tower crane, the characteristics of various machines available must be considered against the requirements imposed by the loads to be handled and the surroundings in which the crane will operate. Other factors such as weights, dimensions and lift radius of the heaviest and largest loads must also be considered, which necessitate the use of an optimization technique such as GA to solve such problem.

Many studies have been developed to optimize the location of tower crane, based on lifting time and cost. A mathematical model was developed by Rodriguez-Ramos and Francis [1] to find optimum location of a crane in a construction site. The technique considers radial and angular crane movement of construction materials. The objective of the model is the minimization of the total crane transportation cost between crane and the construction supportive facilities that are serviced by the crane. This model is actually locating the position of the crane hook when waiting between movements. At the same time, the calculation of lifting time does not take into consideration the vertical motion of tower crane hook and the simultaneous movement between the angular and radial hook movement as reported by Abouel-Magd [2].

This model was then adopted by Choi and Harris [3] to develop a mathematical model for optimizing tower crane location. However, they considered that the angular and radial movements were carried out simultaneously with the hoisting movement. Instead of locating the optimal hook waiting position for a crane, they suggested to locate the optimal location of a tower crane to serve the predetermined supportive facilities (Leung and Tam [4]).

On the other hand, a graphical model was developed to help user to select the location of tower crane by Cooper [5], and its methodology was by examining user suggested locations to meet a number of technical requirements while considering available machine. Shapira and Goldenberg [6] criticized that this system anyhow provides guidance, and all decisions are left to the user's discretion.

One major important model is developed by Zhang et al. [7] as it was a major key step for all following studies. A mathematical model is developed for location optimization for a group of tower cranes using Monte Carlo simulation approach. This mathematical model involves three steps, such as initial location generation model, task assignment model and single tower crane location optimization.

Tam et al. [8] used the main function that was developed by Zhang et al. [7] to develop a GA model to optimize supply locations around tower crane based on least cost. However, the optimization was focused on supply locations not the crane. Son [9] developed a GA model to optimize the location of tower crane using Zhang et al. [7] model for computing hook travel time. The study was restricted only for precast construction projects. Alkriz and Mangin [10] developed a GA model for optimizing the location of tower crane and construction facilities. In this study, the loading and unloading time modeled by Zhang et al. [7] was neglected because they do not vary when the crane and facilities location changes within site from one place to another.

One modern application for the model is the one introduced by Huang et al. [11]; this model applied the mixed-integer linear programming technique to solve the problem of locating tower crane and facilities. Another application is the GIS-BIM model that has been developed by Irizarry and Karan [12] for optimizing a group of tower cranes. The main objective of the model is to locate a group of tower cranes to reach minimal amount of conflicts. Lien and Cheng [13] proposed a new model for optimizing tower crane location and the quantity of materials to be transported from supply to demand areas using particle bee algorithm (PBE). The technique is applied on former models by Tam et al. [8] and Huang et al. [11] and the results show that PBA has better performance than particle swarm optimization (PSO) and bee algorithm (BA). However, the selection of tower crane location is limited to predetermined locations.

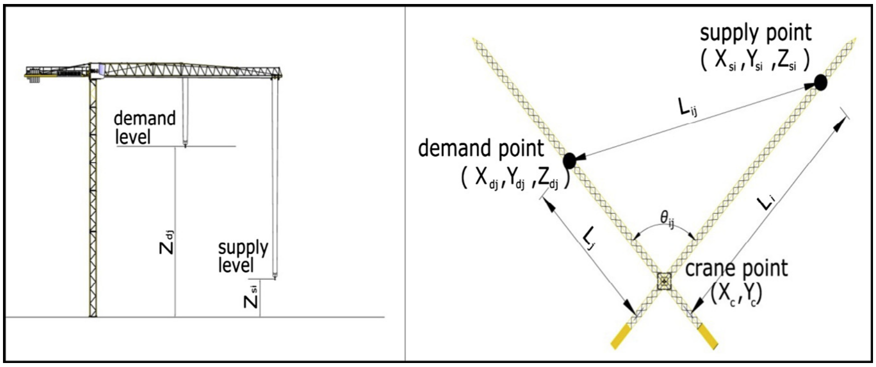

Figure 1 Movements of crane hook [7].

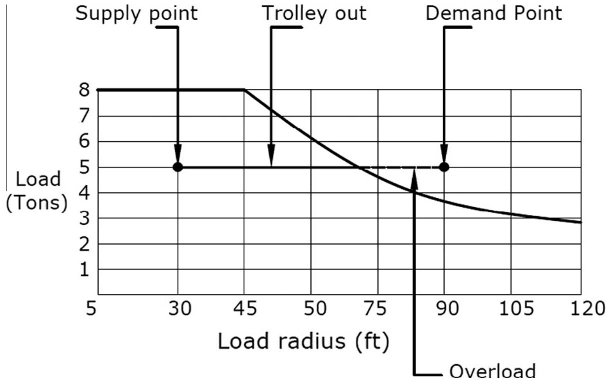

Figure 2 An example for tower crane load chart.

2. Tower crane location optimization model

While recent studies were concerned mainly about applying new optimization and modeling techniques to solve the under study problem, this paper aimed mainly at improving the optimization model by updating the approach of calculating the required time for tower crane to perform its assigned tasks. These improvements are derived by adding more factors into account such as the interrelated relation between all possible crane positions, number of cycles for each task and the vertical hook velocity related to the loads been transported.

This model can be used to locate a tower crane for small to medium projects that need single tower crane. Depending on tower crane capacity and configurations, some modern tower cranes jib length reaches 100 m with 110 m hook reaching height making the crane capable to serve an area more than 30,000 m^2 and its hook to reach about 30 floors. Thus, proposed model can be applied in projects such as hospitals, industrial buildings, residential buildings, educational facilities, halls, religious buildings.

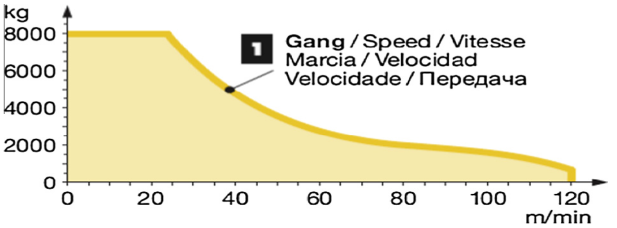

Figure 3 Vertical hoisting velocity for Liebherr 132 EC-H8 Litronic.

2.1. Model assumptions

Decision variables of the proposed model are the coordination of tower crane base center in construction site. The following assumptions are considered in developing the model:

a. Temporary facilities are divided into rectangular shape areas in order to simplify the problem. Each area named facility and the centroid of this area is the supply (loading) point.
b. Buildings are divided into rectangular shape areas, each area named working zone and the centroid of this area is the demand (unloading) point.
c. All site constraints such as roads, staff caravans and car parking are considered facilities but without loads.
d. Temporary facilities and site constraints locations are assumed fixed.
e. Tower crane is assumed to have a square area, which refers to the tower crane fixing base. Shapiro and Shapiro [14] mentioned that this area can either be taken from tower crane database in the case of using a chassis base or be calculated from the soil report data in the case of using reinforced concrete mast base.
f. The allowable load, lifted by the crane from supply point to demand point, is varied due to tower crane type, radius and bucket size.
g. Tower crane is free standing and its height must reach all required demand points' heights. The use of climbing tower crane will limit the solutions to the buildings areas and perimeters only which conflicts with model constraints that will be discussed later in this chapter.
h. Waiting times of crane such as loading and unloading delays will not be modelled because they do not vary when the crane location changes within the site from one place to another [10].

2.2. Transportation time for performing task

As mentioned in Zhang et al. [7] model, if (X_{si}, Y_{si}, Z_{si}) and (X_{dj}, Y_{dj}, Z_{dj}) refer to the location of supply point (S_i) and demand point (D_j) respectively and the crane area centroid

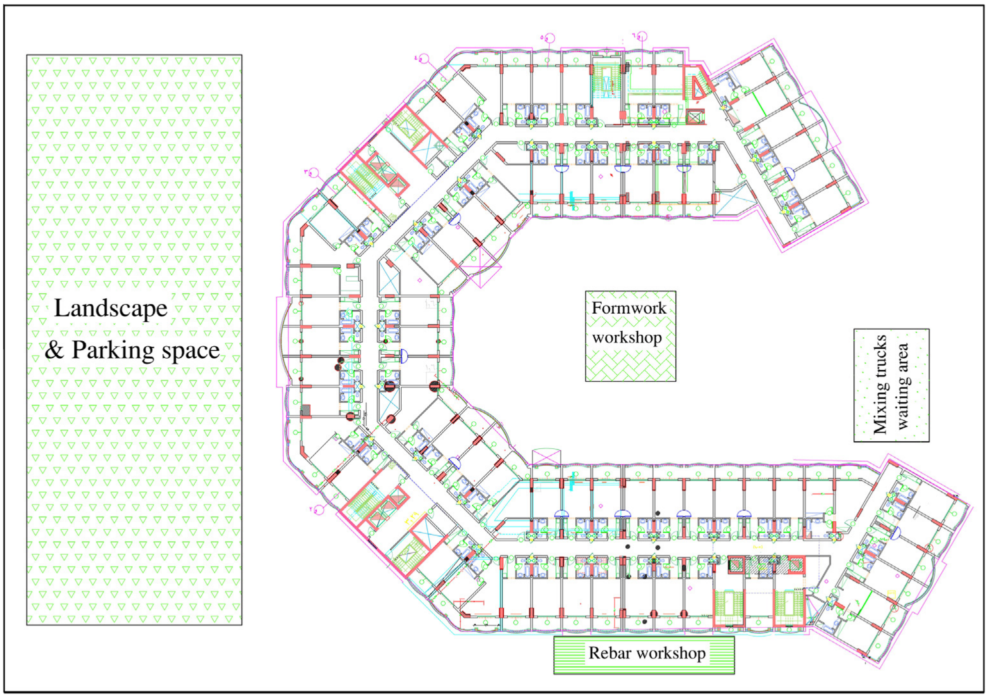

Figure 4 General construction site plan for the example project.

located at (X_c, Y_c) as depicted in Fig. 1, all distances between crane, supply and demand points can be calculated as follows:

$$L_i = \sqrt{(X_{si} - X_c)^2 + (Y_{si} - Y_c)^2} \qquad (1)$$

$$L_j = \sqrt{(X_{dj} - X_c)^2 + (Y_{dj} - Y_c)^2} \qquad (2)$$

$$L_{ij} = \sqrt{(X_{si} - X_{dj})^2 + (Y_{si} - Y_{dj})^2} \qquad (3)$$

$$Z_{ij} = |Z_{si} - Z_{dj}| \qquad (4)$$

$$\theta_{ij} = \text{Arccos}\left(\frac{L_i^2 + L_j^2 - L_{ij}^2}{2 \cdot L_i \cdot L_j}\right) \qquad (5)$$

Time for hook horizontal travel T_{hij}, taken to move from a supply point (facility) S_i to a demand point (building zone) D_j, can be calculated as follows:

$$T_a = \frac{|L_i - L_j|}{V_a} \qquad (6)$$

$$T_w = \frac{\theta_{ij}}{\omega} \qquad (7)$$

$$T_{hij} = \max(T_a, T_w) + \alpha \cdot \min(T_a, T_w) \qquad (8)$$

Time for hook vertical travel T_{vij} taken to move from a supply point (facility) S_i to a demand point (building zone) D_j, can be calculated as follows:

$$T_{vij} = \frac{Z_{ij}}{V_v} \qquad (9)$$

According to Zhang et al. [7], hook travel time between supply (i) and demand (j) T_{ij} can be calculated as in following equation. This formula will be updated to represent a new factor as stated at the model improvements described later.

$$T_{ij} = \text{Max}(T_{hij}, T_{vij}) + \beta \cdot \text{Min}(T_{hij}, T_{vij}) \qquad (10)$$

Kogan [15] mentioned that an experienced driver performs simultaneous operations during 76% of the total duration of the cycle. Hence, the value of parameter α is assumed as 0.25 unless otherwise stated, and β is assumed as 1.0, i.e., the hook moves consecutively in two planes [7].

2.3. Improvements to former models

2.3.1. Number of cycles

While this term was assumed given information in previous studies, it is considered a variable in the proposed model. This consideration is based on the change of tower crane capacity for each task according to its location in the construction site. Number of cycles required for each building zone storey depends on the quantity needs to be handled from supply point to demand point and the capacity of tower crane according to its configuration represented by its load chart as shown in Fig. 2.

Hence, number of task cycles can be calculated as follows:

$$N_{ij} = \frac{Q_{ij}}{C_{ij}} \qquad (11)$$

2.3.2. Vertical velocity of crane hook

Vertical hoisting velocity (V_v) is measured in metres per minute and varies according to the load needs to be lifted; the greater the load the lower the velocity is. Fig. 3 represents the vertical hoisting velocity chart from the (Liebherr 132 EC-H8 Litronic) tower crane data sheet. This implies that the time needed for lifting the load will vary due to the amount of the load allowable for each task, which depends on the capacity of the crane described in previous clause. Hence, tower crane lifting time should be divided into loaded time and unloaded time. This

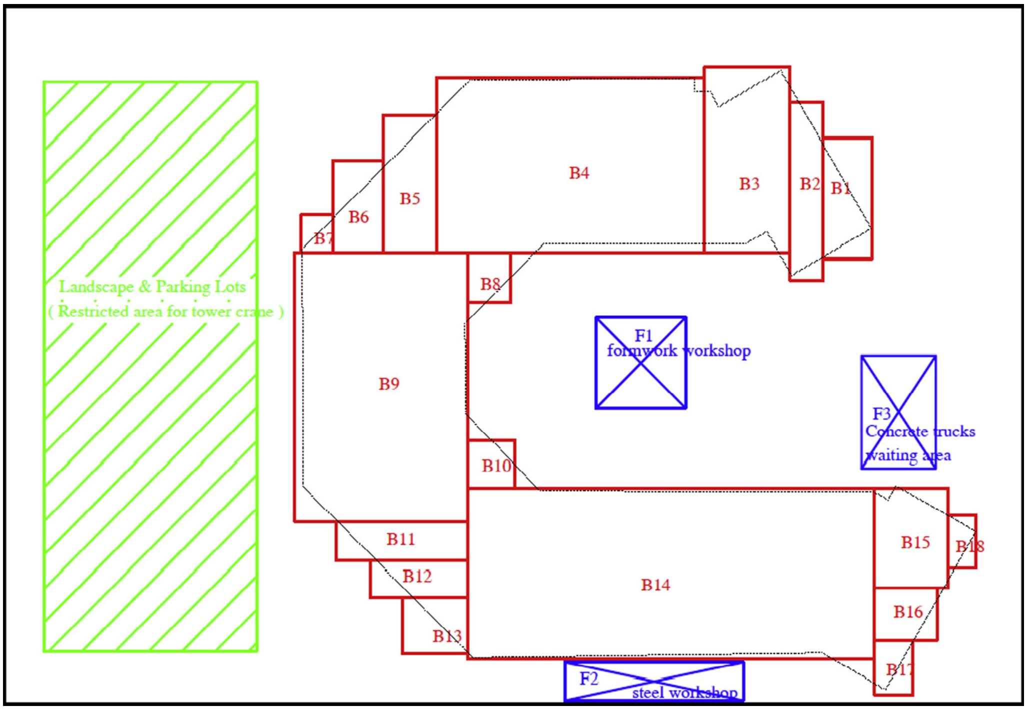

Figure 5 Equivalent layout for the example project.

modification will lead to new formulae for calculating tower crane cycle time as in the following equations:

$$T_{vij} = \mathrm{TL}_{vij} + \mathrm{TU}_{vij} \tag{12}$$

$$\mathrm{TL}_{vij} = \frac{Z_{ij}}{V_{vl}} \tag{13}$$

$$\mathrm{TU}_{vij} = \frac{Z_{ij}}{V_{vu}} \tag{14}$$

Table 1 Reinforced concrete skeleton material requirements for each storey.

Facility	F1	F2	F3
Material	Wood (formwork)	Reinforcement steel	Concrete
Material unit	m^3	ton	m^3
Unit weight	0.55 ton/m^3	7.85 ton/m^3	2.2 ton/m^3
B1	3.84	3.02	21.21
B2	6.4	5.03	35.39
B3	17.44	13.7	96.5
B4	58.71	46.13	324.97
B5	7.64	6.01	42.29
B6	4.26	3.35	23.54
B7	0.79	0.62	4.35
B8	2.58	2.03	14.27
B9	58.63	46.07	324.56
B10	2.73	2.14	15.07
B11	5.71	4.49	31.58
B12	3.76	2.96	20.82
B13	2.2	1.73	12.17
B14	87.9	69.07	486.57
B15	9.16	7.2	50.7
B16	4.07	3.2	22.5
B17	2.48	1.95	13.72
B18	1.79	1.41	9.88

Loaded hook time TL_{ij} can be calculated using the following equation:

$$\mathrm{TL}_{ij} = \mathrm{Max}(T_{hij}, \mathrm{TL}_{vij}) + \beta \cdot \mathrm{Min}(T_{hij}, \mathrm{TL}_{vij}) \tag{15}$$

Unloaded hook time TU_{ij} can be calculated using the following equation:

$$\mathrm{TU}_{ij} = \mathrm{Max}(T_{hij}, \mathrm{TU}_{vij}) + \beta \cdot \mathrm{Min}(T_{hij}, \mathrm{TU}_{vij}) \tag{16}$$

In conclusion, the formula for calculating cycle time between supply (i) and demand (j) T_{ij} can be derived by the addition of Eqs. (15) and (16) as follows:

$$T_{ij} = Max(T_{hij}, \mathrm{TL}_{vij}) + \beta.Min(T_{hij}, \mathrm{TL}_{vij}) + Max(T_{hij}, \mathrm{TU}_{vij}) + \beta \cdot Min(T_{hij}, \mathrm{TU}_{vij})$$

since $\beta = 1$, then

$$T_{ij} = \mathrm{TL}_{vij} + \mathrm{TU}_{vij} + 2x\,T_{hij} \tag{17}$$

2.3.3. Tower crane base system

As stated in Shapiro and Shapiro [14], a freestanding tower crane requires a base mounting that is either weighted with ballast or anchored to a massive structure that can resist overturning moment. This static base might be an undercarriage

Table 2 Best GA parameters for the under study problem.

Parameter	Best value
Number of Generations	15
Population size	40
Crossover rate	60%
Termination tolerance	(1e−2)
Crossover function	(two point)
Selection function	(Stochastic uniform)
Mutation function	(Adaptive feasible)

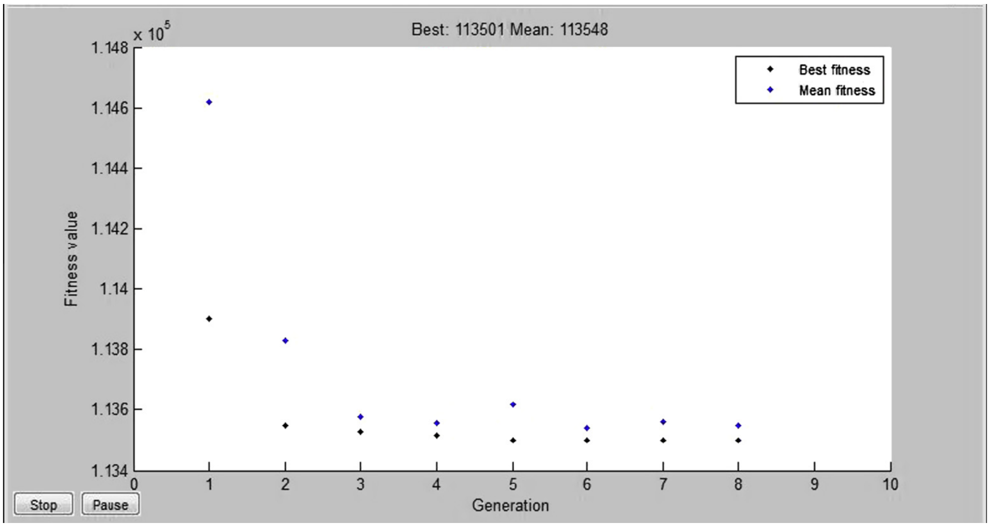

Figure 6 GA performance for the under study problem.

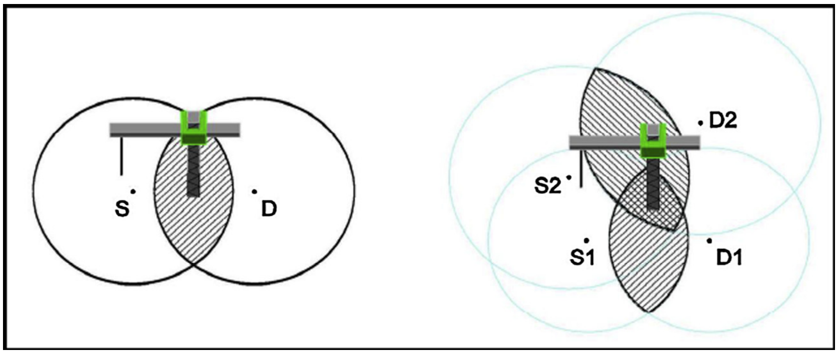

Figure 7 Feasible task area for supply (*S*) and demand (*D*) points for single task and multiple tasks [12].

carrying ballast blocks or a frame anchored to another structure; it could also be a concrete spread footing, a pile cap, or a concrete block tied down with rock anchors. Therefore, modeling tower crane as point could result in incorrect solution by locating the crane at an unsuitable area that is unavailable for its base.

In order to overcome this issue, crane base is modeled as an area constraint. Thus, it is necessary to maintain no overlap between crane base area and any supply or demand area by applying the following constraint equation:

$$\max\left(\left(|X_c - X_{si}| - \frac{L_{xc}+L_{xs}}{2}\right), \left(|Y_c - Y_{si}| - \frac{L_{yc}+L_{ys}}{2}\right)\right) \geqslant 0 \quad (18)$$

$$\max\left(\left(|X_c - X_{di}| - \frac{L_{xc}+L_{xd}}{2}\right), \left(|Y_c - Y_{di}| - \frac{L_{yc}+L_{yd}}{2}\right)\right) \geqslant 0 \quad (19)$$

3. Numerical example

A five Star Hotel construction project is selected to apply the proposed model. The project is established in 13,300 m^2 consisting of 14 storey hotel building (area = 4000 m^2), swimming pool and parking as shown in Fig. 4. The model is applied on the reinforced concrete work for the main building skeleton, which requires at least three basic temporary facilities such as: (i) formwork workshop, (ii) reinforcing steel workshop and (iii) concrete mixing station (either onsite or not).

In order to find a suitable tower crane type and location, the layout needs to be presented in accordance with model assumptions. Therefore, an equivalent layout is considered to increase the accuracy of calculations by dividing the main building into 18 separated rectangular areas, which have the same total area of the building. The tower crane used at this project is Liebherr 110 EC-B 5 with 51.1 m free standing height and 55 m radius.

The equivalent layout can be presented as shown in Fig. 5. Material handling task for each storey requires delivering 280 m^3 formwork, 220 ton reinforced steel and 1550 m^3 concrete. Table 1 lists task requirements for each storey's demand areas.

3.1. GA model

GA has found significant use in solving optimization problems with discrete variables and complex cost and constraint functions (Son [9]). Recently, research shows that GA is robust and has the capability to efficiently search complex solution space. The robustness of GA is due to its capabilities to locate the global optimal. Therefore, GA is less likely to restrict the

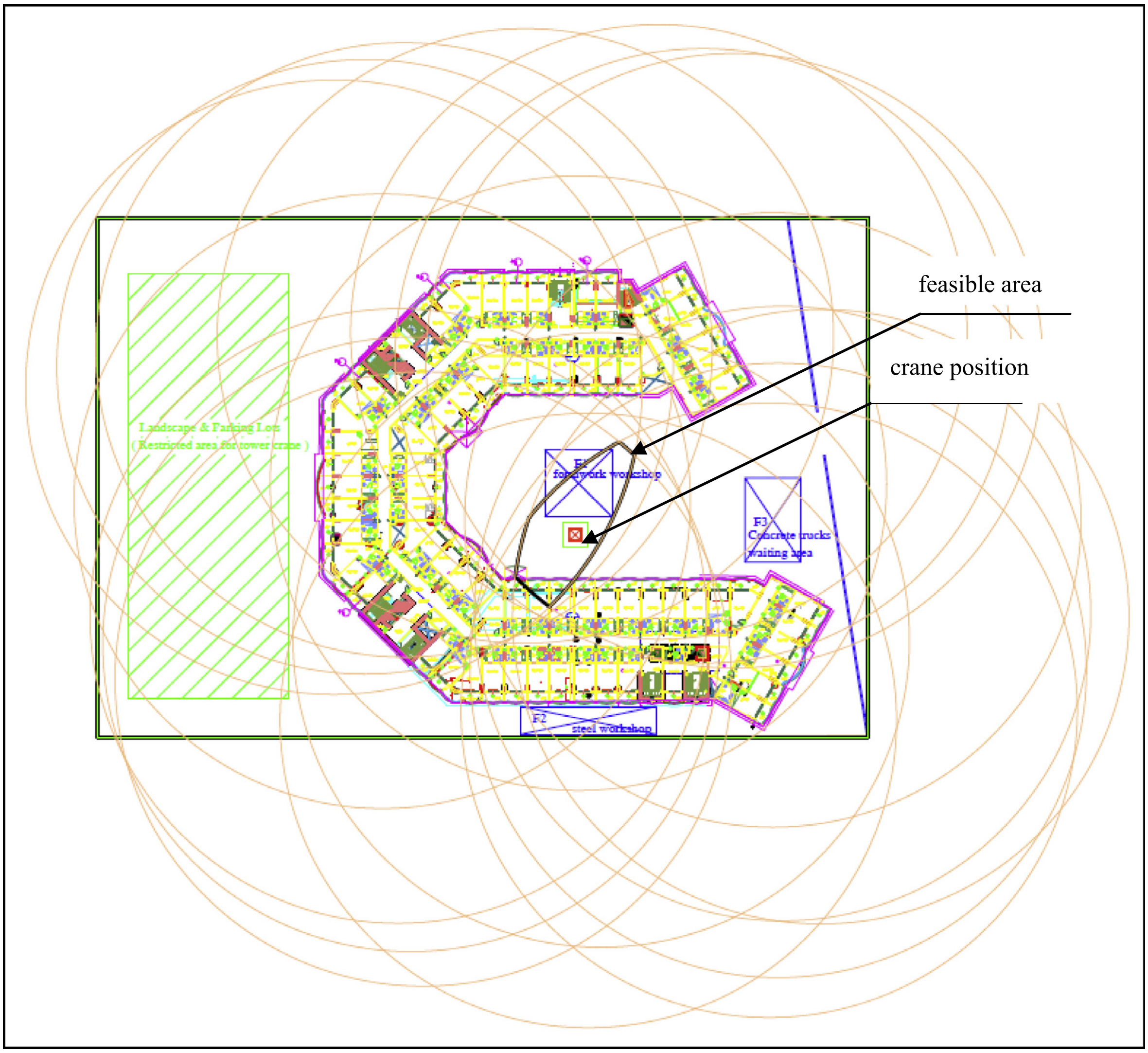

Figure 8 Feasible area for selected crane.

search to a local optimum compared with point to point movement, or gradient descent optimization technique [16].

Having all the data entered, the GA optimization model can be applied. Matlab optimization toolbox is used to represent the proposed GA model. Sensitivity analysis is performed on GA parameters in order to test them through different scenarios to obtain most suitable set of parameters for the problem as listed in Table 2. Best fitness value gained by the GA solver after 8 generations is 1,13,501 min at crane coordination (85.24, 37.58) as shown in Fig. 6.

In order to test results gained by the developed model, feasible area for the selected crane is generated as discussed by Irizarry and Karan [12]. As depicted in Fig. 7, to transport a load between supply point (*S*) and demand point (*D*), the tower crane should be placed within the intersection of two circles describing operating areas for *S* and *D*.

The size of this oval shaped area is determined by the crane's lifting capacity, the length of its jib, and the distance between *S* and *D*. This area is called feasible task area. Hence, feasible area for the crane used for this project can be obtained as shown in Fig. 8.

The selected tower crane location as resulted by the model is within the feasible area that has been determined graphically. Other indicator for the accuracy of the calculations is comparing the resulted total time with the one calculated manually. Results have been almost the same with a very small difference because of the high accuracy of the programme in performing interpolation when dealing with charts such as crane load and vertical hoisting velocity.

4. Conclusion

Developing a model for optimizing tower crane location is in progress since the last 30 years. What this study mainly concerned about is improving the model by updating the approach of calculating the required time for tower crane to perform all of its assigned tasks.

The proposed model is developed based on improving former models by taking into account many factors that have been neglected such as the variation in vertical velocity of tower crane jib. Other important improved part in the calculations is the method of calculating number of cycles needed for each task based on tower crane capacity for each location, which has been assumed fixed in previous studies. Moreover, tower crane base system is also represented in order to deal with crane as an area not as point to increase the reliability of the model.

Further improvements of the model can be carried out to expand the scope of the study by applying different optimization approaches such as ant colony optimization (ACO), particle swarm optimization (PSO), shuffled frog leaping (SFL) and bees algorithm (BA) to the new model and conducting a comparison among them in order to assess the most suitable technique for the problem.

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