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A Computer-based Model for Optimizing the Location of Single Tower Crane in Construction Sites

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Abstract*— The tower crane is a basic machine for lifting and transporting materials and devices. The construction process for buildings and many engineering fields' needs transporting different materials and equipments in a short period, what makes tower cranes necessary. Selection of type and location of tower cranes used in constructing a building is an important issue in planning the construction operations. This paper aims at assisting the project planner in the selection of type and location of tower crane to be used in the construction site. The objective is to minimize the total transportation time. Genetic Algorithms optimization technique is used to solve such a problem. A numerical example is presented to explain the optimization technique.

Index Terms— **Genetic Algorithms Model, Site Layout, Tower Crane Optimization.**

I. INTRODUCTION

The aim of planning crane usage is to gain the most profit at minimum time and cost. Site planner needs to make sure that the crane is utilized on the site in best way, which means that the crane will not left idle between tasks.
Since Tower crane position affects directly on the project duration and cost; it is important to develop an improved model that delivers better values for tower crane position based on the least time required for the lifting operation. The calculation of time required for lifting operation by a tower crane is a complicated process because it depends on many factors which are affected by each other. Solving this problem by traditional methods such as mathematical models is very difficult and not accurate because they cannot take all relevant factors into account, which makes the optimization model the best method for such a problem. Crane location models have evolved over the past 40 years. Warszawski (1973) [13] established a time-distance formula by which quantitative evaluation of location was possible. Furusaka and Gray (1984) [5] presented a dynamic programming model with the objective function through the hire cost, but without the consideration of location. Gray and little (1985) [6] optimized crane location in irregular-shaped buildings while Wijesundera and Harris (1986) [14] designed a simulation model to reconstruct operation times and equipment cycles when handling concrete. Farrell and Hover (1989) [4] developed a database with a graphical interface to assist in crane selection and location. Choi and Harris (1991) [2] introduced another model to optimize single tower crane location by calculating total transportation times incurred. Emsley (1992) [3] proposed several improvements to the Choi and Harris model. Zhang et al. (1996) [11] developed a stochastic simulation model to optimize the location of a single tower crane, and then in (1999) [12] they developed mathematical model for location optimization for a group of tower cranes by using the Monte Carlo simulation approach. Alkriz and Mangin (2005) [1] developed a new model for optimizing the location of tower crane and construction facilities using GA. Shehata et al. (2005) [10] applied the mathematical model developed by Zhang et al. (1999) [12] in a time-cost trade off study to find the best position of tower crane based on least cost. Huang et al. (2010) [7] used the mixed-integer linear programming technique to solve the problem of locating tower crane and facilities, using the same equations developed by Zhang et al. However, some factors have been neglected in these models such as return time calculation of crane hook, the capacity of tower crane for each supply position and the base area of tower crane. Hence, it is necessary to develop a more realistic improved model based on the former models and adding more constraints and factors to the problem.

II. MODEL ASSUMPTIONS

The following assumptions considered in developing the model:
1- Tower crane referred to as square area which refers to the tower crane base.
2- The allowable load lifted by the crane from supply point to demand point is varied due to tower crane type, radius and bucket size.
3- Geometric layout of all supply and demand areas is predetermined.
4- Tower crane is free standing and its height can reach all required demand points heights.

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5- Waiting times of crane such as loading and unloading delays will not be modeled because they do not vary when the crane position changes within the site from one place to another.

III. MODEL DESCRIPTION

In this study, a construction site is modeled in Cartesian coordinates, where crane, buildings and facilities are described by their centroid positions. Two steps are involved in determining the type and optimal position of tower crane. First, an initial selection process of tower crane radius is performed. Second, an optimization model is applied to the selected tower crane in turn to find an exact crane location taking into account all problem constraints.

A. Initial Selection of Tower Crane Radius:

Tower crane radius must exceed half of maximum distance between supply and demand points, the minimum radius can be calculated by using (1), (2)

$$Lij = \sqrt{(Xsi - Xdj)^2 + (Ysi - Ydj} \qquad (1)$$

$$Rmin = (\frac{Lij\,(maximu)}{2})*1.10 \qquad (2)$$

Where Lij=distance between supply (i) and demand (j), Xsi, Ysi, Zsi = coordinates of supply points, Xdj, Ydj, Zdj = coordinates of demand points. Rmin = minimum radius of tower crane. Lij(maximur = maximum distance between all supply and demand points.

B. Optimization Model

In order to perform the proposed model, three steps must be followed to calculate total time of selected position. First, check all problem constraints. Second, calculate number of cycles related to this position. Finally, calculate total time of tower crane for the selected position.

1- Problem Constraints

Considering a set of locations for the crane, the crane must be able to reach all supply and demand points; hence it is important to check that the distance between crane and supply or demand points are within the range of crane jib (R). It is expressed as:

$$R \geq max\ (Li, Lj) \qquad (3)$$

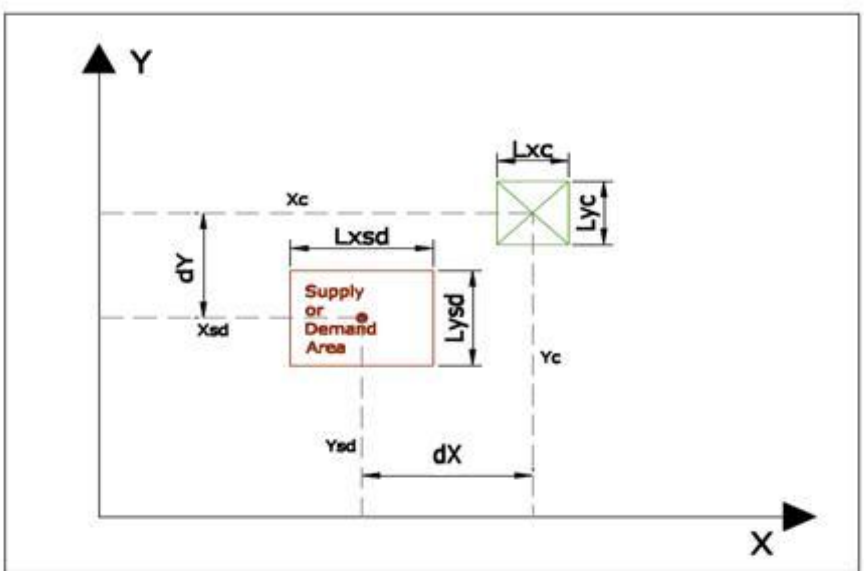

Fig. (1) Overlapping area between crane and supply or demand

Also the maximum height of buildings must not exceed the allowable crane free standing height (Hc), it can be expressed as:

$$Hc \geq max\ (Hi, Hj) \qquad (4)$$

As the crane assumed to operate free standing; it is necessary to validate that overlap will not occur between crane area and any supply or demand area in this layout.

If (Xc, Yc) and (Xsd, Ysd) refer, respectively, to the locations of centroid of crane base and demand or supply points. The constraint can be described as: (see Fig. 1)

$$max\ ((dx-(Lxc+Lxsd)/2),(\ dy-(Lyc+Lysd)/2) \geq 0 \qquad (5)$$

$$dx = abs(Xc-Xsd) \qquad (6)$$

dy = abs(Yc-Ysd) (7)

Where: (Lxc, Lyc) : dimensions of tower crane base area, (Lxsd, Lysd) : dimensions of supply or demand area.

2- Calculation of Number of Cycles

In former studies, the number of cycles was assumed to be fixed for all crane positions whereas in real situations it varies from one place to another. The number of cycles depends on the quantity that needs to be handled from supply point to demand point and the capacity of tower crane which changes for each position. Number of cycles required for each building zone storey (Nij) can be calculated as follow:

$$Nij = \frac{Qij}{Capacit} \quad (8)$$

Where:

Qij = quantity of material to be handled from supply (j) to demand (i)

Capacity ij = capacity of crane from crane load chart (see Fig. 2), which depends on the type of crane, driving units and radius for lifting. The radius can be considered as the maximum value of Li and Lj multiplied by 1.10 because the crane operator could maneuver around any sudden obstacle. In case of transporting fresh concrete, brick, cement, etc. the capacity in equation (6) should not exceed the bucket size provided onsite.

3- Calculation of Hook Travel Time

In order to deliver loads, the crane hook must move in horizontal and vertical directions, while horizontal movement is performed by both the crane jib and hook. Vertical movement is done only by the hook in horizontal-jib tower crane and by the jib in luffing-jib tower crane.

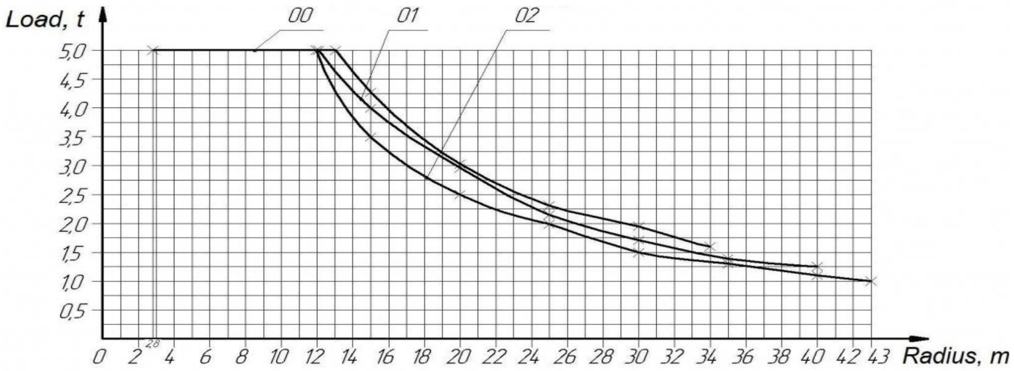

Fig. (2) Tower crane load chart [9]

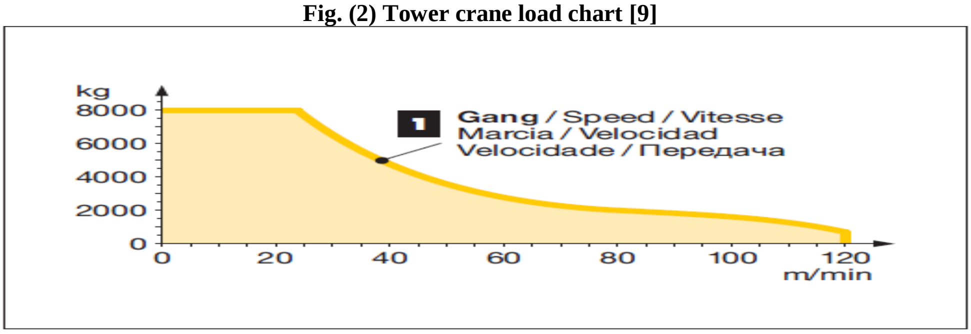

Fig. (3) Vertical hoisting velocity for Liebherr 132 EC-H8 Litronic [9]

Zhang et al. (1999) [12] developed a mathematical model to calculate the hook travel time in transporting construction materials from supply to demand points. In this paper the same equations will be used except the equation for calculating vertical hook time which will be modified to take into account the variation of hook velocity due to the lifted load.

The horizontal travel time is the summation of time for radial and tangential movement, which can be calculated by (9),(10).

$$Ta = \frac{|Li -}{V_a} \quad (9)$$

Tw = (10)

Where: Ta= time for trolley radial movement, Tw= time for trolley tangent movement, Va= radial velocity of trolley (m/min), w= slewing velocity of crane jib (r/min), Li = distance between crane point and supply point, Lj = distance between crane point and demand point, θij= angle between Li and Lj and can be calculated as follow:

θij = Arccos ((Li2 + Lj2 – Lij2) / (2 x Li x Lj)) (11)

Hence, total horizontal time(Thij) can be calculated as:

Thij = max(Ta , Tw) + α.min (Ta , Tw) (12)

Where α is horizontal simultaneous movement parameter and its value is assumed 0.25 (Kogane 1976) [8].

Vertical travel time depends on vertical velocity which varies according to the amount of load to be carried; Fig. (3) shows the vertical hoisting velocity curve for a tower crane.

The time for hook vertical travel Tvij, taken to move from a supply point (facility) Si to a demand point (building zone) Dj, can be calculated as in next equations:

Tvij = TLvij + TUvij (13)

TLvij = [illegible] (14)

TUvij = $\frac{Z}{V}$ (15)

Where: TLvij = vertical hoisting time when the hook is loaded, TUvij = vertical hoisting time when the hook is unloaded, Zij = vertical distance between demand point and supply point, Vvl & Vvu = vertical hoisting velocity of loaded and unloaded hook (m/min).

Because of the variation of hook velocity, travel time must be calculated in two cases, the travelling case (while the hook is loaded) and the return case (while it is unloaded).

Loaded hook time TLij can be calculated by (16):

TLij= Max (Thij , TLvij)+β . Min (Thij , TLvij) (16)

Unloaded hook time TUij can be calculated by (17):

TUij= Max (Thij , TUvij)+β . Min (Thij , TUvij) (17)

Where: β: simultaneous movement parameter in vertical and horizontal planes and its value assumed 1.0 (Kogane 1976) [8].

Total cycle time (Tij) is the summation of vertical and horizontal time, it can be calculated as follow:

Tij = TLij + TUij

Tij = Max (Thij , TLvij)+β . Min (Thij , TLvij) + Max (Thij , TUvij)+β . Min (Thij , TUvij)

since β = 1, then

Tij = TLvij + TUvij + 2 x Thij

Tij = Tvij + 2 x Thij (18)

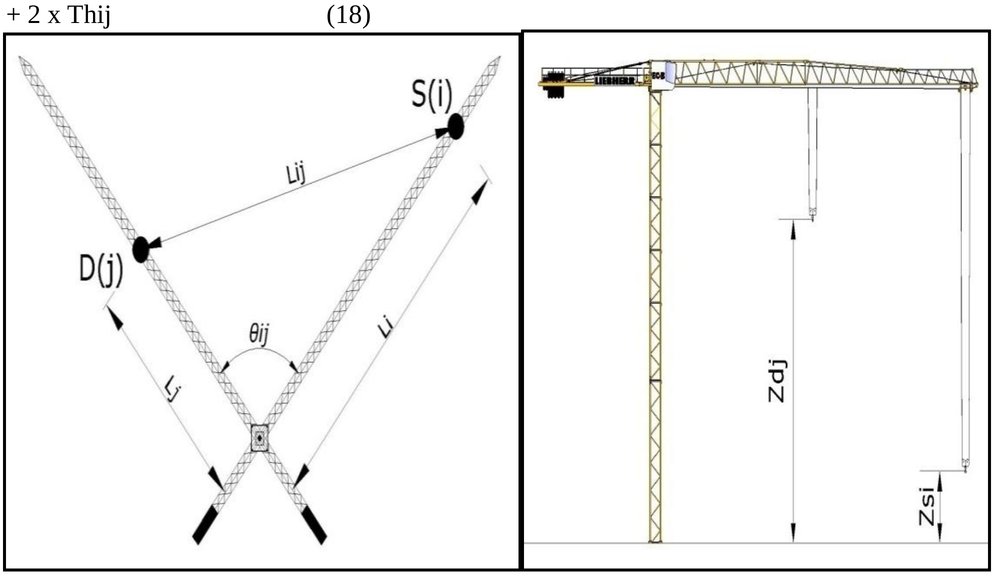

Fig. (4) Distance between crane positions with supply and demand points [12]

Total transportation time

Total transportation time of tower crane is the summation of transportation times for each building, and can be calculated as follow:

$$Ttotal = \sum_{m=1}^{P} Tbuilding\ (m) \quad (19)$$

Where: P: number of buildings in site.

The time needed for each building is the summation of transportation times for each storey:

$$Tbuilding\ (m) = \sum_{n=1}^{R} Tstorey\ (n) \quad (20)$$

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Where: R: number of storeys for building (m).

Tstorey (n) = Nij x Tij (21)

Where: Nij : number of cycles to perform the lifting task between supply (i) and demand (j) associated to storey (n), Tij : cycle time between supply (i) and demand (j) associated to storey (n).

The objective function used for the optimization model can be formulated using (9) to (21) as follow:

$$Ttotal = \sum_{m=1}^{P} \sum_{n=1}^{R} \left[\frac{Qij}{Capacit} \right] . \left[\frac{|Zsi - Z_d|}{Vvl} + \frac{|Zsi - Z_d|}{Vvu} + 2.\left(\frac{\left|\sqrt{(Xsi-X)^2+(Ysi-Y)^2} - \sqrt{(Xdi-X)^2+(Ydi-Y)^2}\right|}{Va} \right. \right. +$$
$$\left(Arccos\left(\left(\sqrt{(Xsi-X)^2+(Ysi-Y)^2}\right)2 + \left(\sqrt{(Xdi-X)^2+(Ydi-Y)^2}\right)2 - \left(\sqrt{(Xsi-Xdj)^2+(Ysi-Ydj)^2}\right)2 / \left(2 . \sqrt{(Xsi-X)^2+(Ysi-Y)^2} . \sqrt{(Xdi-X)^2+(Ydi-Y)^2}\right)\right)/w\right] \quad (22)$$

IV. GENETIC ALGORITHMS MODEL

The algorithm first randomly generates a population of fixed size (initial population). Each individual solution of the population is assessed with regard to the objective functions. The algorithm iteratively produces new generations of population which evolve through selection, crossover and mutation [1]. An optimization tool is developed in this paper (using MATLAB) in order to help planners and engineers in finding the best position of tower crane for any project that matches this study assumptions. This tool is tested through multiple situations applied on numbers, areas, positions and quantity of materials of project buildings and facilities. The usage of this tool is going to be described in the following example.

V. NUMERICAL EXAMPLE

A residential compound project is selected to apply the described GA model on it. The project consists of five residential buildings and an outdoor swimming pool. The crane task in this project is the reinforced concrete skeleton and the brick walls. Total area of the project is 10000 m2. Project data such as buildings, facilities and quantity of materials to be handled are entered to the developed computer tool as shown in Fig. (5).

The procedures of using the tool are as follow:

A. Entering project data

The input data are entered in the front window of the user interface. These data are divided into 5 groups as illustrated in Fig. 5.

1- Project Data: These data represent the general information about the project and the dimension of working space to be used at the calculation phase.

2- Demand (Buildings): The information about demands (coordinates, dimensions, number of floors and floor height) is to be presented in this table.

3- Supplies (Facilities): The information about supplies (coordinates, dimensions and material type) is to be presented as the same as demands.

4- Quantity of Materials: This table will be activated when all previous data are entered and by pressing at its push button.

5- Project Layout: After entering previous data and by clicking save; a simple layout of the project is going to be drawn at the top left area of the page.

B. Entering materials properties

The material push button will open a new window to define all materials for the project and all relevant data that will be useful for the calculation, (see *Fig.6).*

C. *Selecting* a suitable tower crane

By clicking on the (suggest suitable crane) button; the program will apply equation (2) to make a list of all suitable cranes from the list of defined cranes. The selected crane for this project is Liebherr 130 EC-B 6,(as shown in Fig.7).

D. Running the GA optimizer tool

The program report page contain a push button named "Find crane position using GA"(Fig. 9); by clicking on it the GA operators will run and during the running a graphic window is going to be opened showing the progress of generations created and the best and mean fitness value produced by fitness function,(see Fig. 8).

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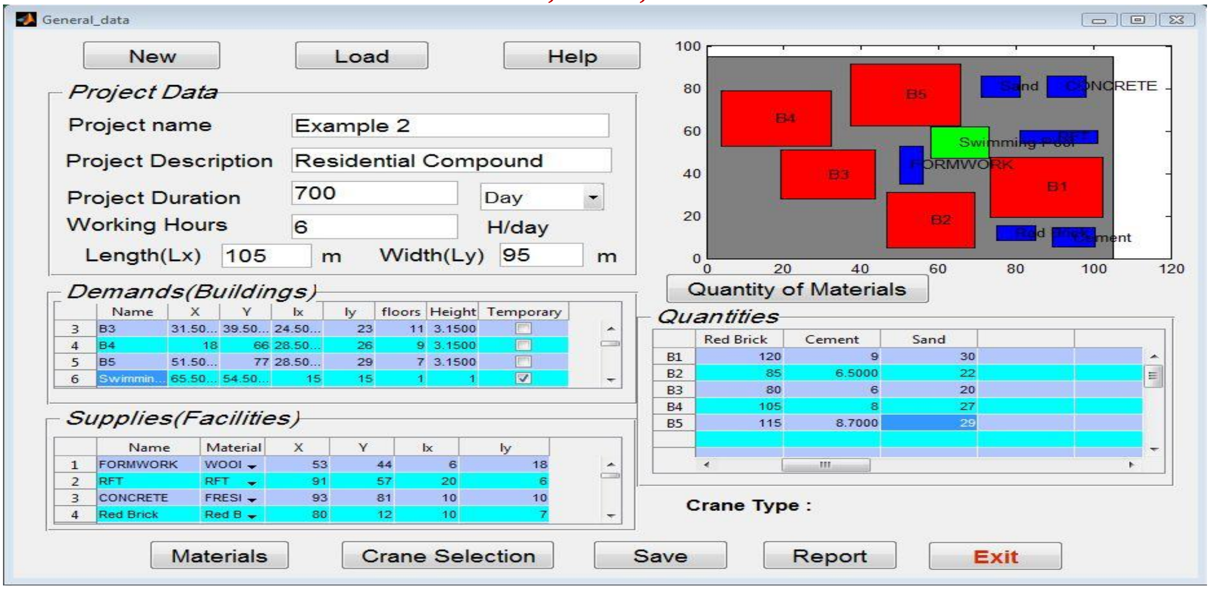

Fig. (5) Project data

Fig. (6) Materials properties

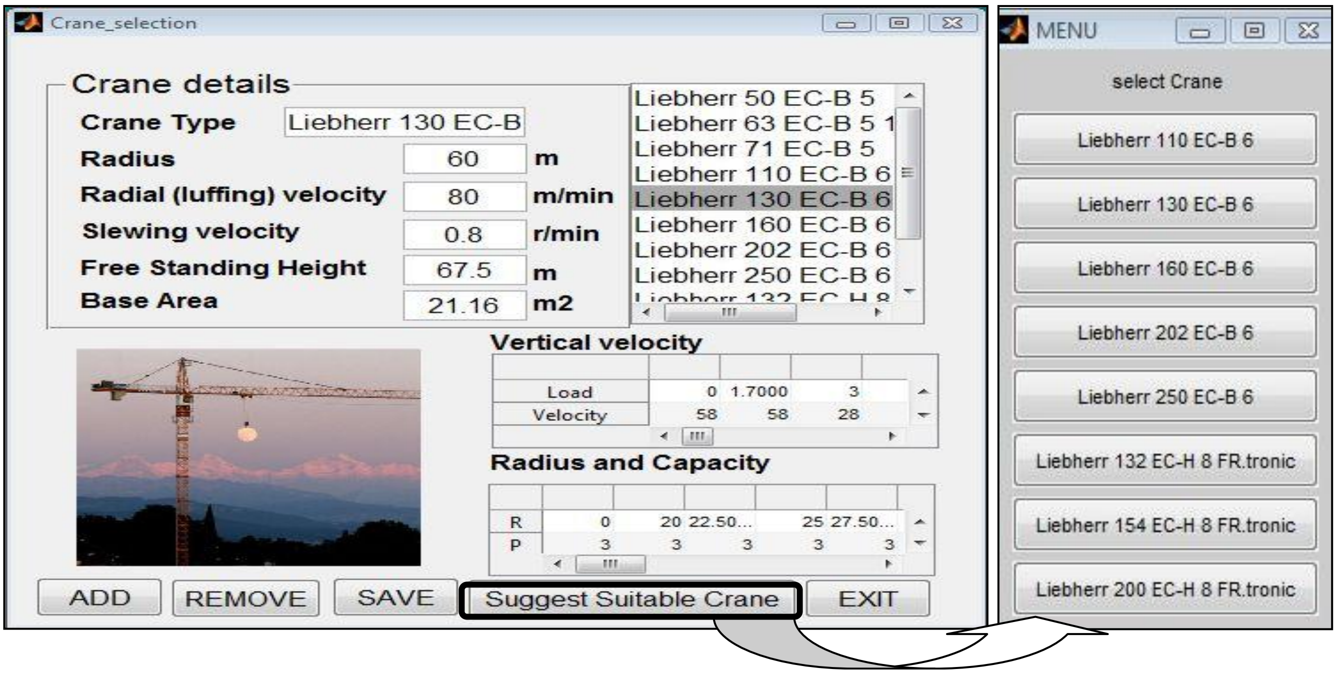

Fig. (7) Crane selection

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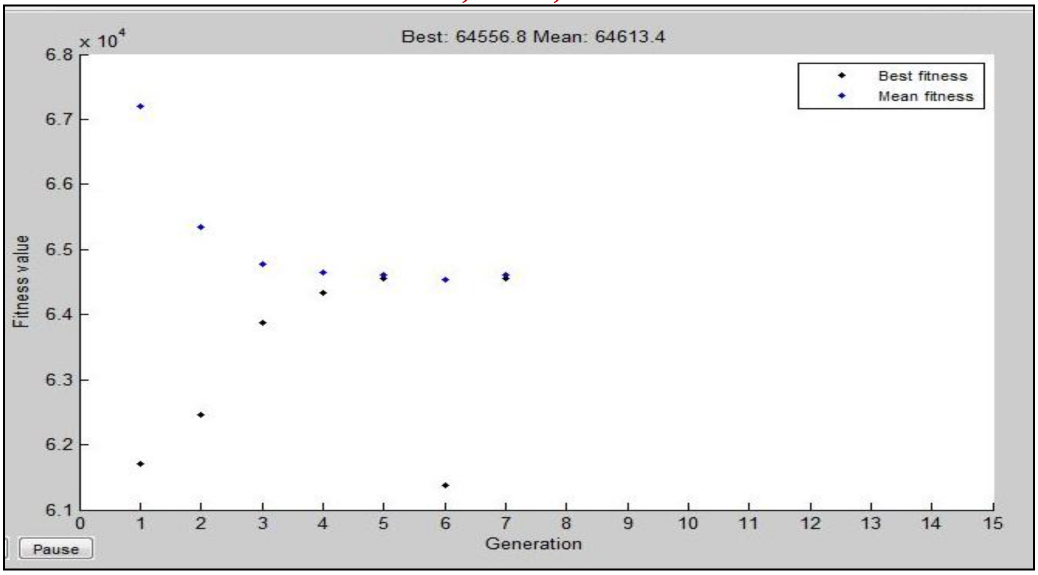

Fig. (8) GA performance

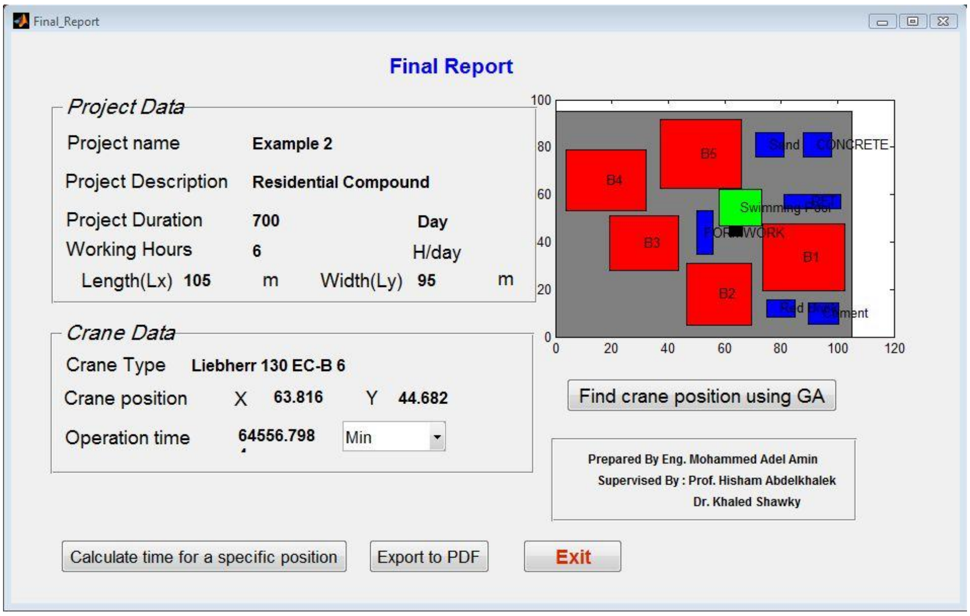

Fig. (9) Final Report window

In order to compare between results gained by the proposed model and the traditional methods, an initial location is selected according to the feasible area for the crane described in (Zhang et al. 1999) [12] model. By considering all area constraints of this project, the final feasible area will be as in Fig. (10), whereas the initial coordinates for tower crane will be approximately at the center of this area (63.60, 38.70). The total time of tower crane to perform all project tasks at the initial position, calculated manually by applying the time calculation formulas, is 73090 minutes. On the other hand, and according to the proposed model, the optimal location of tower crane is (63.8 , 44.7), and the total time is reduced to 64556 minutes, which means a 12 % reduction in total time was obtained using the model.

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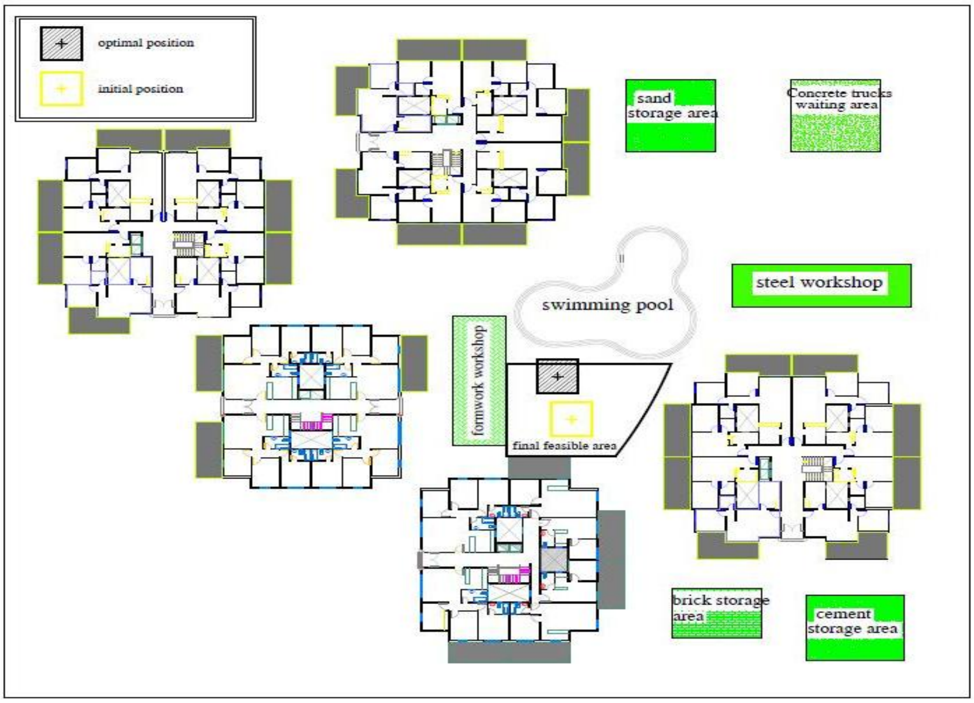

Fig. (10) Initial and Optimal Tower Crane Locations on Project Layout

In order to perform a tuning process for the GA parameters; several tests were carried out and the best results were gained when applying parameters listed in Table (1).

Table (1) GA parameters

PARAMETER	BEST VALUE
Number of Generations	15
Population size	40
Crossover rate	60%
Crossover function	(two point)
Selection function	(Stochastic uniform)
Mutation function	(Adaptive feasible)

VI. CONCLUSION

Developing a model for optimizing tower crane position has been going since the last 40 years, what this paper mainly concerned about is improving the method of calculating time and the objective function used for GA model. The most important improved part in the calculations is the number of cycles needed for each task, which has been assumed to be fixed in the previous studies. By this update, the usage of developed model is applicable in reality and can be profitable in planning and scheduling phase. Another main improvement is taking into account the variation of hook vertical hoisting velocity due to the lifted load. At the same time, a computer tool is developed aiming to help planners and engineers to solve single tower crane location problem for a construction project. Future work will be extended to optimize all construction site facilities as well as using multiple tower cranes at the same time. To perform this improvement, there must be several operations to be performed before running the model, such as applying a task assignment model to assure the balanced workload at all cranes and study the confliction between all cranes to be used at the construction site.

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