A NEW MODEL FOR OPTIMIZING THE LOCATION OF CRANES AND CONSTRUCTION FACILITIES USING GENETIC ALGORITHMS

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In the field of construction, the positioning of cranes and facilities within construction site is a very important phase for construction companies with major stakes on cost and duration of any construction project. The application of a quantitative approach to determine the optimum positions for cranes and facilities is highly desirable for construction site planning. Actually, this task tends to be carried out manually by experienced engineers during preparation and organization phases of construction. This operation is complex and difficult to achieve because of the complexity of knowledge and the considerable amount of facilities used and the interactions between them. Sometimes there is a great risk when implementing poor choices, which are expensive for the company; with wasted time and substantial loss of productivity. Therefore, overcosts could be the result of non relevant choices for locating facilities. This paper aims to develop an optimisation system and decision support tool, based on Genetic Algorithms (GAs) to determine the optimal position for the cranes and the facilities in construction sites. This tool depends on spatial modelling of the construction site, with site's elements and optimisation method based on genetic algorithms. Several criteria of evaluation are proposed in order to assess the performance of different solutions. These criteria can be: the total hook travel times of cranes, the severity of conflicts between cranes and the balancing workloads of cranes. Optimisation results are shown to illustrate the proposed model and appropriate conclusions are drawn.

Keywords: Construction site layout, Genetic algorithms, Modelling, Optimisation, Productivity.

INTRODUCTION

Recently, the marketing competition drives building companies to make good organization and management for their construction sites in order to ensure good productivity and new margins of profitability. The layout planning of a construction site, which defines types, quantities and position of equipment (cranes, concrete batching plant) and essential facilities (storage areas, prefabrication yards…) has a significant impact on the overall productivity and cost effectiveness of a construction project. The position of cranes and facilities within a site is still carried out by engineers/planners based only on their experience and common sense, usually without taking into account quantitative criteria (Tam and Arthur, 2002).Therefore, the resulting site’s layout is not optimised and may lead to additional costs, waste of labor time and materials, inefficient use of resources and increased possibility of conflicts.

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Several researchers have been attempting to solve this problem. Rodriguez-Ramos and Francis (1983) developed a mathematical model to establish the optimal location of a single tower crane within a construction site. The model aimed at locating the best position of the crane hook when waiting between movements. Choi and Harris (1991) proposed a mathematical model to determine the most suitable single-tower crane location. The model aims to optimize the position of a tower crane that yields the least transportation time between the crane and the construction facilities. Zhang and Harris (1996) developed a stochastic simulation model to optimise the location of a single-tower crane. This pattern is not quite representative to the real world of construction site because it has not taken into account the interactions between the crane and the construction facilities, which considerably influences the crane location in the final result. Arthur and Tam (1999) developed a quantitative model for predicting hoisting times of tower cranes for public housing construction using Artificial Neural Network (ANN) and Multiple Regression Analyses (MRA).

Other studies realized in the United States, have shown that U.S manufacturing companies spent between 20% and 50% of total operating expenses for material handling and that a good position for facilities can reduce these costs by at least 10% to 30%. In most of the above research works, the problem of positioning cranes and construction facilities within a site has been handled in a partial and incomplete way. Most of these studies were focused to determine a single crane position, but they don't take into account the case of a large construction site where it is necessary to use several cranes. In other words, existing models were tended to be oversimplified from the real world and site conditions were not considered.

MODEL DESCRIPTION

In this study, a construction site is modelled in Cartesian coordinates, where cranes and facilities are described by their positions. A facility, as storage yard, generally can be any shape and be positioned in any orientation on the site. For simplicity, it is assumed, that all facilities are represented by rectangles while the cranes are represented by squares. The width and the area of each facility are given as inputs, and the facility can be built around the coordinates within possible location.

From site data and geometric shape of the building, each storey of the building plan is divided into working zones which are represented by the coordinate of their centroids.

The possible locations and/or feasible areas for locating the cranes and facilities are determined from the site map with consideration of the length of crane jib, required size of the facility and other site constraints. Hence, the list of all available locations for each facility can be obtained by dividing the feasible area with a chosen step.

Constraints problem

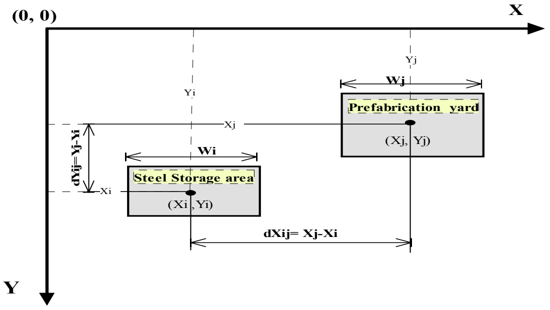
For a set of locations for the crane and facilities, the crane lifting capacity is decided by a radius-load curve where the greater the load the smaller the crane's operating radius. Hence, the locations of both construction facilities and working zones of permanent building must fall within the permissible weight–radius circle of the crane. Since building zones are fixed, attention is focused on the possible locations of facilities and crane. This constraint imposes that the distance between crane and working zones Di, and between crane and construction facilities Dj, should be within the length of crane jib (lcr) or the lifting capacity radius. It is expressed as:

$$Max\ (Dj\ ,Di\ ) \leq lcr \qquad [1]$$

As several facilities can be positioned within the same feasible area, it is necessary to validate that overlap will not occur between two facilities in this layout.

If (Xi, Yi) and (Xj, Yj) refer, respectively, to the locations of centroid of facility i (steel storage area) and facility j (prefabrication yard), (see Figure1)

The non overlapping constraint between the two facilities i and j can be expressed as:



$$MAX\begin{bmatrix}(dXij-\frac{Wj+Wi}{2})\times(dXij+\frac{Wj+Wi}{2}),\\(dYij-\frac{Aj}{2Wj}-\frac{Ai}{2Wi})\times(dYij+\frac{Aj}{2Wj}+\frac{Ai}{2Wi})\end{bmatrix}\geq 0 \quad [2]$$

$$dXij = Xj - Xi \quad [3]$$

$$dYij = Yj - Yi \quad [4]$$

Figure 3: Overlapping area between two facilities

Wi, Wj : width of the facility i and j;   Ai, Aj: required area for facility i and j;

dXij, dYij : distances between the centroids of facility i and j.

This kind of modelling allows the use of the coordinates of geometric shape centroid for each crane and facility as the optimisation variables. The performance of a site construction layout is measured through quantitative criteria presented below.

CRANE HOOK TRAVEL TIME: (CRANE CHARGE)

The crane charge (time) can be obtained by calculating the total handling times for necessary elements per construction floor cycle.

Calculation of the number of crane cycles for a building zone

Each storey of building plan is divided into working zones in accordance with the duration of construction floor cycle. Each building zone is generally composed of vertical works (walls, columns) and horizontal works (beams, floors). Each work can be achieved by some realisation tasks. Hence, the number of crane cycles of a building zone is obtained by cumulating the number of cycles of different works performed in this designed zone. To calculate the number of cycles of a task, two values of data are required: firstly, the total task quantity necessary for the zone; secondly, the volume of handling loads for each craning cycle (handling hypothesis). The first value is given as input from building data while the second can be calculated for each set of locations of crane and facilities in function of lifting capacity of crane in a layout. For example, in table 1, the crane is able to lift a maximum quantity of the task “*handling of formworks*” equal to (4.6 ml) of forms in accordance with the crane position and its loads- radius curve in this layout. Table 1 show, for a group of locations for crane and facilities, the total number of crane cycles necessary to realize the building zone 1.

Table 1: Number of crane cycles for the building zone 1

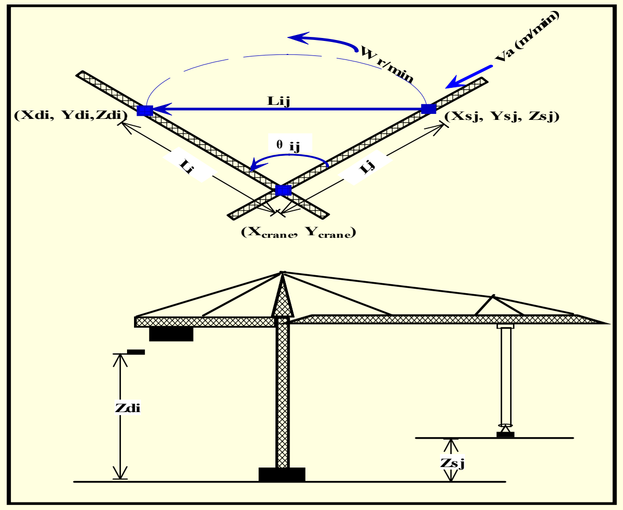
Works and their associated tasks being in the building zone (1)	Quantity of task		Hypothesis of handling	Number of crane cycles
Work 1: Casting of concrete walls	**37**	**ml**		**35**
Task 1 : Handling of formworks	40	ml	4.6 ml	9
Task 2: Handling of reinforcing bars	1.5	tons	1 tons	2
Task 3: Handling of dummy	5	units	1 unit	5
Task 4 : Casting of concrete	19	m^3	Bucket of (1) m^3	19
Work 2: Casting of concrete slabs	**72**	**m²**		**17**
Task 1 : Handling of predalles	72	m²	12 m²	6
Task 2 : Handling of reinforcing bars	1	tons	1 ton	1
Task 3 : Casting of concrete	10	m^3	Bucket of (1) m^3	10
Number of crane cycles for the working zone 1 in a one building storey			**(Cycles)**	**52**

Calculation of hook travel time

In this study, the hook travel time of a craning cycle modelled here represents the horizontal and vertical travel time rather than the whole travel time of the cycle. The loading and unloading delays will not be modelled because they do not vary when the crane and facilities position changes within the site from one place to another.

When the crane operates, its hook has to move to a building zone and from a facility to enable tasks to be performed. For a crane located at the point (X_{cr}, Y_{cr}), the time for hook horizontal travel Thij, taken to move from a supply point (facility) Si to a demand point (building zone) Dj, can be calculated as following, (Figure 2).

The formulas that permit the calculation of time Thij between two points i and j are:



$$Li = \sqrt{(Xdi - X)^2 + (Ydi - Y)^2} \qquad [5]$$

$$Lj = \sqrt{(Xsj - X)^2 + (Ysj - Y)^2} \qquad [6]$$

$$Lij = \sqrt{(Xdi - Xsj)^2 + (Ydi - Ysj)^2} \qquad [7]$$

$$Ta = \frac{|Li - Lj|}{Va} \qquad [8]$$

$$T_w = \frac{1}{W} \times \left(\frac{Lij^2 - (Li^2 + Lj^2)}{2 \times Li \times Lj} \right), \qquad [9]$$

$$(0 \leq Arccos(\theta ij) \leq \pi)$$

Figure 4: Simulation of craning cycle operations

X, Y: coordinates of the centroid of crane; Xdi, Ydi: coordinates of the centroid of building zone i; Xsj, Ysj: coordinates of the centroid of facility j;

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).

The horizontal travel time for each craning cycle between two points i and j (Thij) is given by formula 10, in which the first part take into account a perfect simultaneity of radial and tangential movement while the second part allows to take in consideration the degree of coordination of hook movement in radial and tangent directions.

$$Thij = Max\ (Ta\ ,Tw\ ) + \alpha .Min\ (Ta\ ,Tw\ ) \qquad [10]$$

The coefficient α should be a value between 0 and 1 depending on the skill of crane operators and site conditions. However, experimental surveys realised by Kogan

(1976) have shown that the horizontal simultaneous movement of crane operations in lifting objects is assumed to be 76% of the total duration of the cycle. Hence, the coefficient α in our model is assumed to be 0.25.

The vertical travel time for each craning cycle between two points i and j (Tvij) is given by the formula 11.

$$Tvij = \left| Zdi - Zsj \right| / Vv \quad [11]$$

Vv: vertical hoisting velocity of hook (m/min)
(Zdi–Zsj): vertical distance between the unloading point di and the loading point sj
The total travel time for each craning cycle between two locations i and j is given by:

$$Tij = Max\ (Thij\ , Tvij\ ) + \beta \times Min\ (Thij\ , Tvij\ ) \quad [12]$$

Where, the coefficient ß represent the degree of coordination of hook movements in horizontal and vertical planes. In our model, it is assumed that the crane hook moves consecutively in horizontal and vertical planes. Hence, the coefficient ß is equal to 1.

The total crane hook travel time necessary to realize the zone k can be given by:

$$Tzone\,(k) = \sum_{i=1}^{n} \sum_{j=1}^{m} (2 \times Nij \times Tij\,) \quad [13]$$

n: number of works associated to the zone k; m: number of tasks associated to a work
N i j: number of cycles for task j associated to work i and located in zone k.

Since the number of craning cycles of a task (Nij) is calculated with regard to the crane capacity and the positions of crane and facilities within a site, the value of Nij can be changed from one set of locations of facilities to another set of locations.

The total hook travel time to achieve all works of one building storey is given by:

$$T_{Storey} = \sum_{k=1}^{p} Tzone\,(k) \quad [14]$$

P: number of zones in each building storey.

BALANCED WORKLOADS INDICATOR OF CRANES

In practice, the balanced workloads indicator can be evaluated only in the case of large construction sites for which several cranes are needed to ensure the overall coverage of all demand and supply points. For a configuration of the locations of cranes and facilities, it is very probable that one crane might be overburdened while others are idle. The indicator of balanced workloads is applied to the working zones that can be reached by more than one crane to minimise the overcharge of the cranes.

For that, a matrix of accessibility is created to define the accessibility of each crane to working zones, in which $\delta_{i,j}$ is a decision variable defined as follows:

$$\delta ij = \begin{cases} 1 & \text{if crane i is able to serve building zone j} \\ 0 & \text{otherewise} \end{cases} \quad [15]$$

This indicator can be calculated by the standard deviation of cranes times, from:

$$\sigma_{Tcr} = \sqrt{\frac{I \times \sum_{i=1}^{I} (T_{cr}(i))^2 - (\sum_{i=1}^{I} T_{cr}(i))^2}{I^2}}) \qquad [16]$$

Where: I is the number of cranes used on the site
$T_{cr}(i)$: Hook handling times of the crane i which can be obtained by the formulas 17

$$T_{cr\,(i)} = \sum_{j=1}^{J} (\delta_{ij} \times N_{i\,j} \times t_{cyl(ij)}) \qquad [17]$$

Ni j: number of crane cycles performed in the zone j; J: total number of zones;
$t_{\text{cyl (i j)}}$: time of hook movements of a cycle for the crane i which realize the zone j.

INTERFERENCES INDICATOR BETWEEN CRANES

To measure the possibility of conflict between two cranes, it is assumed that each couple of crane-tasks corresponds to a triangle; their apexes are: location of building zone, facility and crane locations. Thus, the number of intersections between two triangles reflects the severity degree of conflicts. The more intersections the more likely conflicts to appear, hence, the conflict in case 4 is more probable than in case 2.

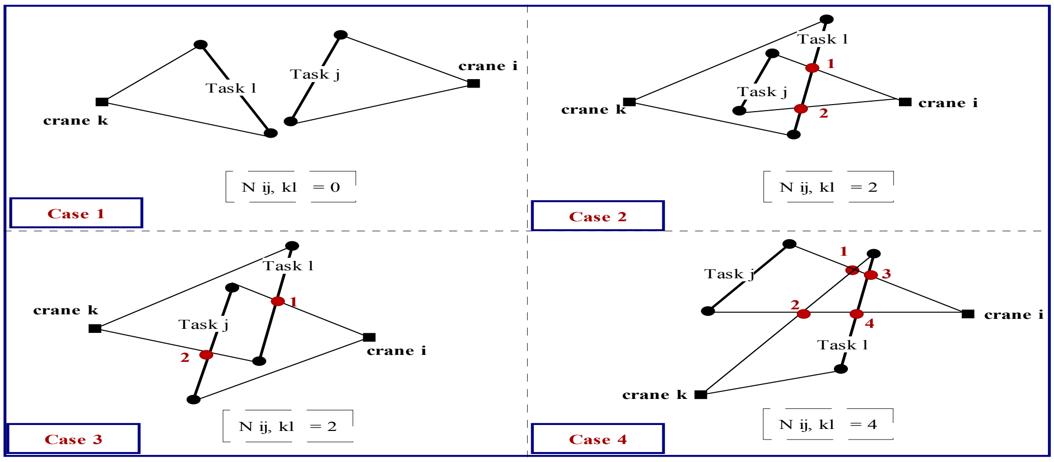


Figure 5 : Severity of conflicts between cranes

Let variable N ij, kl which defines the number of intersections between two triangles, consisting of the two couples: (crane i - task j) and (crane k - task l), respectively. This variable N ij, kl can be calculated according to the logic explained in Figure 3.

The possibility of intersections between two cranes, i and k, proceeding of two tasks, j and l, respectively, is given by formula 18 below,

$$\mathrm{INC}_{\mathrm{ij,kl}} = N_{ij,kl} \times (C_{ij} + C_{kl}) \qquad [18]$$

$\mathrm{INC}_{\text{ij, kl:}}$ indicator of conflict between the cranes i and k resulting from the task j and l
$C_{\text{i j:}}$ number of craning cycles for task j; $C_{\text{k l:}}$ number of craning cycles for task l
Hence, the conflict indicator between two cranes, i and k, for all associated tasks, can be calculated by the following formula:

$$\mathrm{INC}_{\mathrm{i,k}} = \sum_{l=1}^{L} \sum_{j=1}^{J} (N_{ij,kl} \times (C_{ij} + C_{kl})) \qquad [19]$$

J, L: number of the tasks associated to the crane i and crane k, respectively.

The general possibility of conflicts for all cranes and their associated is given by

$$\text{INC}_{\text{total}} = \sum_{i=1}^{I-1} \sum_{k=i+1}^{I} (INC_{ik}) \qquad [20]$$

Where I: is the number of cranes used on the site.

PRODUCTIVITY LABOR

The reduction of crane cycle times, related to optimal positions for facilities, can bring considerable productivity benefits and savings in terms of labor time and construction. A shorter crane cycle means higher labor productivity, because the crews served by the crane will produce the same output in shorter time, so that the entire job will require fewer worker-hours altogether (Rosenfeld 1998). To evaluate the economic value of this aspect, the following assumptions were made.

- For each task, the workers number of a crew working with the crane and served by it at both loading and unloading locations is considered as data input
- The usual time of workers waiting for the crane during the task realisation is rather good than vice versa;
- The labor time of a task considered here is the part of total task labor time for which the crane is simultaneously occupied with the workers.

Hence, for each set of locations of crane and facilities (solution) and with regard to the previous assumptions, the labor cost which is needed to realize the handling tasks in the building zone (z) can be calculated as follows:

$$CL(z) = \sum_{k=1}^{Nz} \mathrm{N_w}(\mathrm{k}) \times T_{cr}(k) \times UL_k \qquad [21]$$

N_w (k): workers number of the crew for task (k); Tcr (k): time of crane necessary to the task (k); UL_k: cost of labor time per worker, per unit time spent by task (k); Nz: number of tasks in the zone (z).

The total labor cost to realize the all zones of one storey is obtained by the formula 22:

$$CL(storey) = \sum_{z=1}^{P} CL(z) \qquad [22]$$

OPTIMIZATION OF SITE FACILITY LAYOUT

The optimisation problem of site facilities layout is characterised by discrete variables with nonlinear objective functions. Thus, the conventional methods such as gradient method are inadequate to solve this kind of problems. Therefore, new model based on genetic algorithms are proposed to handle it taking into account the multi-objective functions such as the ones defined above. GAs are local search methods that belong to the class of stochastic search algorithms. They are based on the mechanics of natural selection and genetics. The first rigorous formulation to the general principle of genetic algorithms was created by Holland (1975) but the success of the method owes much to the work of Goldberg (1989).

In this paper, two formulations of GAs are proposed: The first one concerns site layout having a large size, in which it is needed to use several cranes within the site whereas the second concerns smaller sites for which one crane is able to ensure the realization of works.

Construction site with several cranes

Two types of chromosomes are proposed; the first chromosome is a vector of integer strings containing the position code of cranes and facilities whereas the second is a vector of integer strings containing the crane number which could serve a given handling task. The first chromosome consists of a number of genes which is equal to the number of cranes and facilities. The value of a gene represents the position code of corresponding element of layout chosen randomly from possible positions list. Figure 4 shows an example of chromosome for a site containing: 3cranes, 2 concrete mixers, 2 storage areas, 2 reinforcing bars areas and 2 prefabricated yards.

Facilites (number)	1	2	3	4	5	6	7	8	9	10	11
Chromosome	**13**	**4**	**1**	**8**	**20**	**25**	**5**	**4**	**22**	**7**	**36**
	Cranes			concrete mixers		storage areas		Reinforcing bars area		Prefabricated yard	

Figure 6 : Definition of a chromosome

As several cranes are able to serve a building zone, a second chromosome should be constructed, in which each gene corresponds to a task and takes a value that corresponds to a crane number which can perform it. Thus, the value of each gene is chosen randomly from a list of possible cranes corresponding to this task. Ex: in Figure 5, the task 1 can be served by three cranes; its corresponding gene with the value 2 signifies that crane N°2 is chosen.

Tasks (number)	1	2	3	4	5	6	7	8	… .	N-1	N
Chromosome	**2**	**1**	**3**	**1**	**1**	**2**	**1**	**3**	… .	**1**	**2**
Possible Cranes	1,2,3	1,3	2,3	1	1	2	1,2	1,2,3	… .	1	2,3

Figure 7 : Coding of tasks chromosome

Construction site with one crane

In this case, one crane can be able to ensure the overall coverage of all demand point (working zones) and all supply points (facility locations). Therefore, the chromosome defined in figure 5 does not take place.

GA METHODOLOGY

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.* To go from current generation *k* to the next generation *k+1*, the following steps are repeated for the whole population.

- Selection: A selection by an *elitist* scheme is used to favour the best half of population to construct an intermediate population.
- Crossover: Pairs of Parents are selected from the intermediate population at random. The Crossover operator is applied on them with a probability Pc and new pairs of children are produced.
- Mutation: Individuals are selected from the population according to their fitness. The mutation operator is applied to them with a small probability Pm and mutants are produced. Mutation operator alters one randomly chosen gene of an individual by changing its value.

NUMERICAL APPLICATION

The described GA model was applied to optimise the site facilities layout of a construction project of nine stories. The duration of floor construction cycle is limited by 10 days/ floor. Hence, each floor of building plan is divided into 10 working zones, which are represented by their centroids coordinates and are given in Table 2.

The facilities to be positioned in the site together with their designed numbers, area, width and maximum loads to be lifted away from each facility, are given in Table 3.

Table 2: Coordinates of the centroids of working zones

Zones	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
X(m)	18	27	24	30	36	42	48	51	54	60
Y(m)	10	5	16	16	10	10	14	5	14	10
Z(m)	16	16	16	16	16	16	16	16	16	16

Table 3: Facilities to be located in the site

Number	Facilities	width (m)	Area (m²)	Max. loads (t)
F1	Concrete mixer	7	70	2,9
F2	Formwork and supports storage yard	7	60	3,25
F3	Reinforcing bars and dummy yard	6	60	1
F4	prefabrication yard	8	75	4
F5	Crane	4	16	-

The crane selected for the site is a GTA 90 with vertical hoisting velocity equal (30m/min) and slewing and trolley radial velocity equal to 0.75 tr/min and 25 m/min respectively. The length of crane jib and its lifting capacity are showed in table 4. Table 5 gives the quantities for each type of handling materials between facilities.

Table 4: Radius- load curve of selected crane

Radius (m)	1...23	24	25	27	29	30	33	35	39	40	43	45
Max. load (kg)	4000	3815	3630	3310	3030	2910	2590	2400	2100	2030	1860	1750

GTA 90 : Maximum length of crane jib lcr = 45 m

Table 5: Quantities of handling elements between facilities and building zones

Facilites	Type of lifting loads	Unit	F1	F2	F3	F4	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
F1	Concret	m3				59	29	27	27	26	25	27	25	27	24	25
F2	Formworks	ml					14,91	4,42	6,94	4,76	4,13	10,20	4,64	9,96	4,46	4,06
	Supports	Unit					47,51	49,40	48,96	48,45	49,01	49,01	46,05	49,40	40,65	47,51
F3	Steel bars	ton				4,28	2,15	2,05	2,03	1,94	1,86	2,01	1,88	2,05	1,82	1,83
	Dummy	Unit					4	5	5	5	5	4	4	5	4	4
F4	Prefabricated predalles	Unit					71,26	74,1	73,44	72,68	73,51	73,51	69,07	74,1	60,97	71,26
Z1	Formworks	ml		7,89				31,54								
Z2	Formworks	ml		7,19					28,77							
Z3	Formworks	ml		7,14						28,57						
Z4	Formworks	ml		6,67							26,66					
Z5	Formworks	ml		6,16								24,62				
Z6	Formworks	ml		6,97									27,86			
Z7	Formworks	ml		6,50										26		
Z8	Formworks	ml		7,19											28,77	
Z9	Formworks	ml		6,65												26,58
Z10	Formworks	ml		6,13			24,51									

According to site conditions and the preference of site planners, possible zones were determined to locate the crane and construction facilities within the site. Several tests were carried out to fix the GA parameters. For this example, optimization results were quite satisfactory for a population size of 120 chromosomes running during 140 generations, crossover rate was fixed to 0.80 and mutation rate to 0.20.

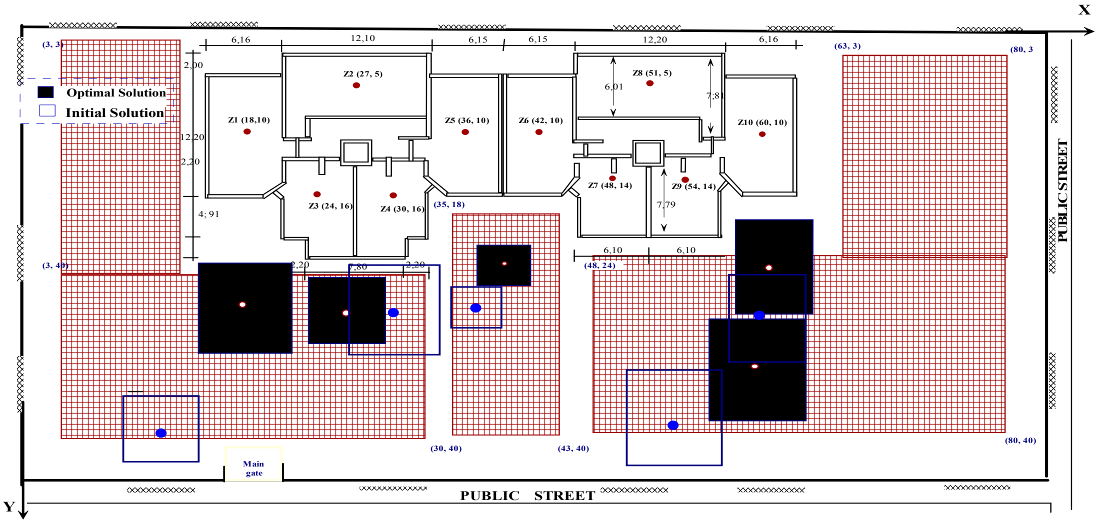


Figure 8 : Optimal construction site facility layout

Table 6 shows that the time of crane hook movements to achieve the handling tasks of one building storey was reduced from 1349 minutes (based on the best layout within the initial population) to 925 minutes (based on the optimal solution), so that, a 31 % reduction was obtained through the use of the GA model. The labor cost for the crew working with crane was decreased from 2250 € to 1542 € (optimal solution) with the consideration that the number of workers of the crew is equal to 4 and the cost of one worker, per unit time is assumed to be (22 €/ Hour).

Figure 6 shows the optimal locations for crane and facilities within the site whereas Figure 7 shows the relationship between the best fitness of the GA population and the number of generations, in which the best solution was obtained after 32 generations.

Table 6: Optimal and initial locations for the site elements

Facilites	**Initial Locations**		**Optimal Locations**	
Crane	X=37m	Y=28m	X=39 m	Y=24 m
Concret mixer	X=30 m	Y=28 m	X=18 m	Y=28 m
Formworks storage area	X=10 m	Y=40 m	X=26 m	Y=28 m
Reinforcing bars area	X=58 m	Y=30 m	X=60m	Y=24 m
Prefabrication yard	X=52 m	Y=40 m	X=58 m	Y=34 m
Hook travel Time of the crane for one building storey	**Fc = 1349,48 min**		**Fc = 925,51min**	
Labor cost (Euros)	**CL(*storey*) = 2250 E**		**CL (*storey*)= 1542 E**	

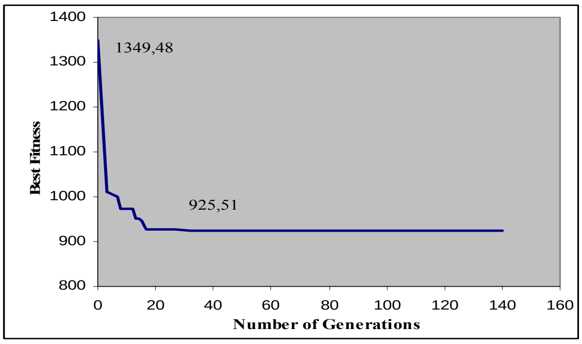


Figure 9: Genetic Algorithm convergence

CONCLUSIONS

The short example developed in this paper demonstrates that the use of GAs for positioning cranes and facilities on construction sites is a very promising approach. It also proves the validation of this research work and demonstrates the application value of the proposed model. A 31 % savings in crane travel time can generate a substantial improvement in labor productivity. Future work will be extended to integrate and hybridise the GA model presented here with 3-dimensional visualization technique to generate and visualize an optimal virtual facilities layout for construction sites.

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