Irregular Dynamic Site Layout Optimization Model

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Abstract When site space is limited, construction site layout planning plays a critical role in the safety and productivity of all operations. As the construction progresses, dynamic planning for the site layout becomes a need to match the project progress. Proper layout planning should take into account the productivity of operations, minimizing the in-situ travel time, the dynamic nature of site operations, and safety regulations implementation on site. This paper is a continuation of the previous work tackling irregular site layout planning, where it presents a new model approach for optimizing the dynamic planning of site layout with safety consideration. This model's algorithm shows high performance in tackling complex projects with limited run time compared to other work in literature. The model showcases an automated mapping tool in conjunction with a dynamic scheduling observing safety to produce the optimized site layout using genetic algorithms. To demonstrate the benefits of the proposed model approach, the case study presented in the "Dynamic Layout of Construction Temporary Facilities Considering Safety" paper is taken as the performance reference to verify and validate the model's output. Examination of the results and the comparative analysis is performed to demonstrate the variance between the outputs of the existing reference model, and this model performed herein.

Keywords Irregular site layout optimization · Genetic algorithms · Automation · Construction management

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R. Gupta et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2022*, Lecture Notes in Civil Engineering 363,
https://doi.org/10.1007/978-3-031-34593-7_25

1 Introduction

The process of properly allocating site facilities during the course of a construction project life cycle with the least cost is known as site layout planning. Several site layout models have been developed with different aspects in mind, such as safety, productivity, and security in an attempt to maximize the overall operation and improve efficiency. It was proven that proper site layout planning can impact the project's objectives; cost, time and quality; therefore, it has gained much attention and the need to be studied at more depth and use diverse methodologies to overcome these challenges.

When planning a site layout there are two types; static and dynamic models. Static model entails that the site's Temporary Facilities (TF) are allocated a specific site space from the beginning until the end of construction. In contrast, the dynamic model allows for the movement of TF throughout the project lifecycle, which could act as an edge to speed up the construction, as the facilities are moved to serve the construction activities more efficiently. The size, shape, and function of TF varies from one construction project to another, and those TF could include but are not limited to warehouses, job offices, workshops, batch plants and equipment such as tower cranes. Site layout planning is not only limited to placement of TFs as close as possible to their desired locations, but it also considers the safety measures. Safety measures are taken into consideration through adopting several strategies; like keeping a minimum safe distance between the fixed facilities and the temporary facilities, minimizing the intersections of the paths to minimize possible construction accidents that could take place.

This paper tackles the challenge of developing a model that would optimize the dynamic construction site layout design for irregular shaped facilities. This paper attempts at filling the gap identified in literature, by presenting a dynamic and time-efficient irregular site layout optimization tool that considers multiple orientations of facilities incorporating safety considerations.

2 Literature Review

Site layout planning has attracted researchers' attention long ago; it has too many variables and considerations that one should keep in mind to plan a site layout that would actually enhance the efficiency. A paper by Elbeltagi et al. [2] is one of the early papers to tackle the site layout planning issue, the authors were one of the first researchers to incorporate safety considerations to the model. They provided safety zones around each facility following the OSHA regulations. Nevertheless they also were the first to incorporate scheduling plan changes throughout the project lifecycle. Elbeltagi et al. used discrete model formulation and modeled regular and irregular shapes, adopting genetic algorithms for the optimization process. This paper has been cited more than 100 times to date.

Abotaleb et al. [1] used genetic algorithm to optimize the site layout problem using mathematical formulations for dynamic shapes like shapes with curves and freeform irregular shapes. Their algorithm shapes facilities in accordance with the available space, which entails that a facility could take several shapes depending on the nearest available free space. The model had some limitations and mainly due to that it only considers cost when finding the near optimal solution. It's also very time consuming due to the high number of constraints, therefore computation is a time intensive task.

Since 2010 safety concern has gained momentum, most recent papers are inclined to include safety considerations in the site layout planning. As Farmakis [3] showed us by incorporating in their objective of minimizing cost while maximizing safety. Also as presented by Xu et al. [4], where they introduced a hybrid multiobjective simulated annealing model that works with two objective functions, one to minimize cost and the other to maximize safety.

Furthermore, this paper addresses the gap referred to by Elbeltagi et al. [2], suggesting the enhancement of a mapping tool for the site layout. Not to fall short of the ethical aspect of taking safety into consideration, we have incorporated the necessary safety measures. Our paper also presents a new approach to defining irregular shapes that accepts modifications.

3 Methodology

3.1 Model General Logic

This model tackles some of the gaps identified in literature as it presents a dynamic and time-efficient irregular site layout optimization tool that considers multiple orientations of facilities and incorporates safety considerations. Genetic algorithms approach is used to solve this optimization problem while maintaining all constraints. The proposed model utilizes excel macros embodied in Evolver to optimize the site layout problem. The model is created in a user-friendly format to ease the user's experience. The proposed model is dynamic in the sense that it can accommodate different schedules for the same project and plans the layout based on the existing fixed facilities at the time and the needed temporary facilities. The model shows good time efficiency in the case study compared to the reference model. This is mainly due to the simplicity of the algorithm in mapping the site layout and defining the constraints. Several models in literature neglected the possible orientations of the Temporary Facilities (TFs) unlike this model, which considers four different orientations of the TFs with 90 degrees variance: (0°, 90°, 180°, 270°).

3.1.1 Safety Considerations

Incorporating safety aspects in site layout planning is a concept first introduced by Elbeltagi et al. [2]. Safety considerations in the model are derived from Elbeltagi's work and are incorporated through two aspects. The first aspect is in defining negative relationships between facilities that constitute a safety hazard if placed close to each other. The user can choose due to safety consideration to place two facilities as far from each other as possible. The second aspect is in defining safety zones. Based on the project requirements, the user can define certain areas to be restricted safety zones (a barricade for example), where no facilities would be placed.

3.2 Model Logic Definition

3.2.1 Site Perimeter Definition

In this proposed model, the site area is modeled as a mesh of square units where every facility is plotted by occupying the square units that best fit the shape of the facility. Sizing the mesh units is important as it determines the accuracy of shape representation (the smaller the mesh unit the more accurate curves and irregularities are presented). However, the smaller the mesh unit size, the more computational capacity is needed when the optimization process is performed. The model utilizes the method of Greatest Common Divisor (GCD) mentioned in literature to determine the smallest applicable unit size. The GCD is the largest integer that divides without remainder all facilities areas.

3.2.2 Irregular Shapes Definition

In formulating the logic of the model, one of the main challenges that surfaced was to accurately model the complexities and irregularities of site facilities shapes. This model developed a unique and a simplified approach to define irregular shapes. Each shape is defined as rows of mesh units and the shape is referenced to the upper left corner of the shape location. Each row is defined through several parameters: The shift of the row starts from the above row's start, number of gaps in the row, first, second … etc. part width (depending on the number of gaps) and width of each gap (depending on the number of gaps). To demonstrate the approach, take a look at the shape defined in Fig. 1. This shape is defined using the proposed model in Table 1.

With this simple shape definition technique, any shape can be defined easily with the four orientations. A simple macro on AutoCAD or any similar software can automatically transform a facility or building drawing into such a definition by counting row by row the mesh units (blocks) that the facility's area is occupying and exporting such information on excel sheet to be the data entry of the model. The scope of developing such a macro is, however, not included in this paper. With the

Fig. 1 Irregular shape example

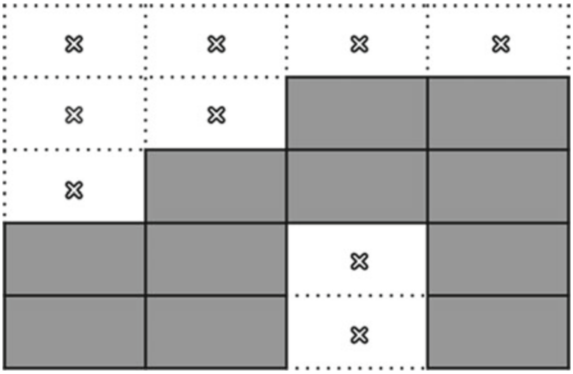


Table 1 Shape definition example of shape in Fig. 1

Shape row number[a]	Shift from above row (units)	No. gaps (units)	1st part width (units)	1st gap width (units)	2nd part width (units)	2nd gap width (units)
1	0	0	2	0	0	0
2	− 1	0	3	0	0	0
3	− 1	1	2	1	1	0
4	0	1	2	1	1	0

[a] Table presenting an irregular shape definition example

shapes being defined, irregular shapes locations can be plotted with determining the index (row No. and column No.) of the upper left corner of each shape.

3.2.3 Distance Calculations

Distance between facilities is calculated as the straight line distance between the Center of Gravity CoG of the irregular shapes (1). Hence the shapes take varying geometries, a method aligning with the shape definition technique is chosen to allocate the centroid of each shape.

Distance Equation

$$d_{ij} = \sqrt{\left(y_i - y_j\right)^2 + \left(X_i - X_j\right)^2} \tag{1}$$

in which

d_{ij} = travel distance between facilities i and j

y_i and y_j = the y coordinate with respect to the total site mesh for facilities i and j respectively

X_i and X_j = the y coordinate with respect to the total site mesh for facilities i and j respectively.

In order to accurately calculate the center of gravity for each of the facilities, the calculations were done in two phases, the first phase was to calculate the center of gravity of each scanned row that forms the facility individually with respect to the total site layout mesh upper left corner Eq. (2) then the same process was done in the vertical direction on all columns forming the shape Eq. (3). The second phase was to calculate the CoG of the entire shape using the sum product of all the subareas multiplied by their respective CoGs, and the sum product is divided by the summation of the areas Eq. (4).

C.o.G (X) Direction Equation for part n of shape i

$$\text{C.o.G}(x) = \frac{\text{Part width}}{2} + \text{column index} \tag{2}$$

C.o.G (Y) Direction Equation for part n of shape i

$$\text{C.o.G}(y) = \frac{1}{2}\text{Unit} + \text{Row index} \tag{3}$$

Shape C.o.G Equation

$$\text{C.o.G}\left(\underline{X_i}\right) = \frac{\sum_{n=1}^{i} \underline{x_i} \cdot A_i}{\sum_{n=1}^{i} A_i} \tag{4}$$

in which

$\text{C.o.G}\left(\underline{X_i}\right)$ = the center of gravity of facility i

$A_{i,n}$ = area of part n in facility i.

3.2.4 Closeness Matrix

A proximity matrix is introduced such that all the relations between the facilities and each other are assigned weights depending on how far or near the facilities need to be which was adopted from the literature [2]. This was done based on the weights scale shown in Table 2.

3.3 Model Formation

3.3.1 Problem Definition and Variables

This model optimizes the site layout with a dynamic nature according to different project milestones. In each milestone the fixed facilities are defined as Available or

Table 2 Proposed closeness relationship weights (adopted from Elbeltagi et al. [2])

Desired closeness relationship	Weight
Necessary to be close	1000
Better to be close	100
May be close	10
Indifferent	0
May be apart	– 10
Better to be apart	– 100
Necessary to be apart	– 1000

Not available indicating whether the facility is built yet or not, and hence should be included in the site plan optimization or not. Temporary facilities also differ according to the milestone and are also considered in the optimization if identified to be needed in the site layout for the particular milestone planned. The model operates by generating possible solutions for the variables, where valid solutions are recorded and enhanced upon. There are two sets of variables in site layout planning. The first is related to the location index of the temporary facility (row No. and column No.) which can take any integer value between 0 and the total number of rows and columns forming the mesh. The second set is related to the orientation of the facility which can take a value of {0, 1, 2, 3} for the four possible orientations.

3.3.2 Objective Function

Site layout plan targets utilizing the site area properly to minimize in-situ travel time and cost while maintaining safety regulations. In the majority of literature, this target is achieved by minimizing the proximity score defined as the multiplication of the facilities distance matrix by the proximity relations matrix (1).

Proximity Score Equation

$$\text{Min} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} d_{ij} R_{ij} \tag{5}$$

in which

n = total number of temporary facilities (TFs)

d_{ij} = travel distance between facilities i and j

R_{ij} = a relative proximity weight reflecting the required closeness between facilities i and j.

3.3.3 Layout Mapping and Constraints

In site layout planning, there are two main constraints that control whether a solution is valid or not; all facilities lay within the site boundaries and that no overlapping exists between facilities (no facility is placed above another). To overcome the complexity of defining such constraints, macros were developed to ease the representation of facilities on the mesh.

Macros are created to graphically represent the site layout. First, one of the developed macros creates the mesh and assigns a value of 1 to all the cells forming the site perimeter. After which another macro is used to plot the fixed facilities, roads, and safety zones available at the chosen time of site layout planning. This is done by incrementing the values of the location cells by 1. A third macro is used with each Evolver trial to test the fitness of each solution and the validity of the constraints. The Temporary facility mapping macro plots the temporary facilities by incrementing the cells of the location of each facility by the value of 10. This results in having the site mesh with the possible values for listed in Table 3. Coding the cells in such a way eases the definition of constraints of site boundaries and overlapping (6) and (7). Figure 2 showcases invalid values representation in site layout that do not meet the required constraints.

Facilities within Site Boundaries Constraint

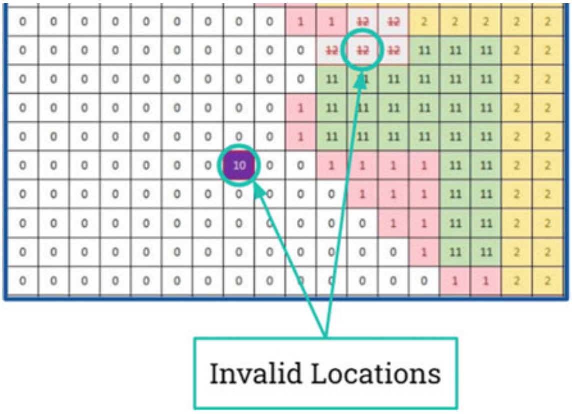
$$\sum \text{cells with count of } 10 = 0 \tag{6}$$

No overlapping facilities Constraint Equation

$$\sum \text{cells with value} \geq 12 = 0 \tag{7}$$

Table 3 Site layout cell possible values

Cell value	Indication
0	Cells outside the layout of the site
1	Cells within the layout of the site but unoccupied by any facility
2	Cell within the layout of the site occupied by a permanent facility
10	Cell outside the layout of the site occupied by a temporary facility
11	Cell within layout of the site and occupied by a temporary facility that is not clashing **(valid location)**
+ 12	Cell within the layout of the site occupied by a temporary facility that overlaps with one or more other facility/ies (temporary or permanent)



0	0	0	0	0	0	0	0	0	1	1	~~12~~	~~12~~	2	2	2	2	2
0	0	0	0	0	0	0	0	0	0	~~12~~	~~12~~	~~12~~	11	11	11	2	2
0	0	0	0	0	0	0	0	0	0	11	11	11	11	11	11	2	2
0	0	0	0	0	0	0	0	0	1	11	11	11	11	11	11	2	2
0	0	0	0	0	0	0	0	0	1	11	11	11	11	11	11	2	2
0	0	0	0	0	0	0	10	0	0	1	1	1	1	11	11	2	2
0	0	0	0	0	0	0	0	0	0	0	1	1	1	11	11	2	2
0	0	0	0	0	0	0	0	0	0	0	0	1	1	11	11	2	2
0	0	0	0	0	0	0	0	0	0	0	0	0	1	11	11	2	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2

Fig. 2 Invalid locations for temporary facilities

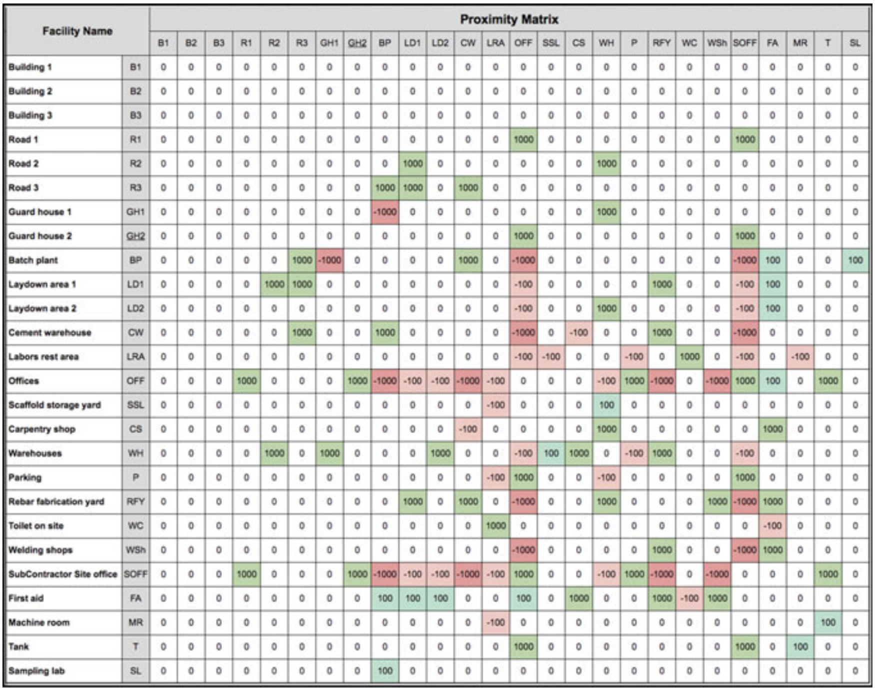
4 Case Study

4.1 Case Study Definition

The case study illustrated here is the same one applied in the paper "Dynamic Layout of Construction Temporary facilities Considering Safety" for the purpose of having a reference and since the model is continuation of the literature work done in that paper [2]. The project is "Tanta University Educational Hospital" with a footprint area of 28,500 m^2 and a scope of three multistory buildings. There are 8 permanent facilities and 18 temporary facilities within different milestones of the project's execution.

4.2 Closeness Matrix

For the case study to be valid, the same closeness (proximity) relationships matrix should be applied on both cases. Looking at the reference of the model in Elbeltagi's work, some of the relationships between facilities were clearly identified. However, some relationships were not mentioned. Hence the missing relationships were selected by industry professionals and incorporated with the known relationships in forming the proximity matrix for the case study (Fig. 3). Elbeltagi's final optimized locations of facilities were tested against the developed proximity matrix to test comparability. The optimized layout score of Elbeltagi's model was in the magnitude of 540,639, while the score applying our proximity matrix was in the magnitude of 764,568. This was considered sufficient similarity of magnitude to adapt the proximity matrix in the case study comparison between the models.



Facility Name		Proximity Matrix																									
		B1	B2	B3	R1	R2	R3	GH1	GH2	BP	LD1	LD2	CW	LRA	OFF	SSL	CS	WH	P	RFY	WC	WSh	SOFF	FA	MR	T	SL
Building 1	B1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Building 2	B2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Building 3	B3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Road 1	R1	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	1000	0	0	0	0
Road 2	R2	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	0	0
Road 3	R3	0	0	0	0	0	0	0	0	1000	1000	0	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guard house 1	GH1	0	0	0	0	0	0	0	0	-1000	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	0	0
Guard house 2	GH2	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	1000	0	0	0	0
Batch plant	BP	0	0	0	0	0	1000	-1000	0	0	0	0	1000	0	-1000	0	0	0	0	0	0	0	-1000	100	0	0	100
Laydown area 1	LD1	0	0	0	0	1000	1000	0	0	0	0	0	0	0	-100	0	0	0	0	1000	0	0	-100	100	0	0	0
Laydown area 2	LD2	0	0	0	0	0	0	0	0	0	0	0	0	0	-100	0	0	1000	0	0	0	0	-100	100	0	0	0
Cement warehouse	CW	0	0	0	0	0	1000	0	0	1000	0	0	0	0	-1000	0	-100	0	0	1000	0	0	-1000	0	0	0	0
Labors rest area	LRA	0	0	0	0	0	0	0	0	0	0	0	0	0	-100	-100	0	0	-100	0	1000	0	-100	0	-100	0	0
Offices	OFF	0	0	0	1000	0	0	0	1000	-1000	-100	-100	-1000	-100	0	0	0	-100	1000	-1000	0	-1000	1000	100	0	1000	0
Scaffold storage yard	SSL	0	0	0	0	0	0	0	0	0	0	0	0	-100	0	0	0	100	0	0	0	0	0	0	0	0	0
Carpentry shop	CS	0	0	0	0	0	0	0	0	0	0	0	-100	0	0	0	0	1000	0	0	0	0	0	1000	0	0	0
Warehouses	WH	0	0	0	0	1000	0	1000	0	0	0	1000	0	0	-100	100	1000	0	-100	1000	0	0	-100	0	0	0	0
Parking	P	0	0	0	0	0	0	0	0	0	0	0	0	-100	1000	0	0	-100	0	0	0	0	1000	0	0	0	0
Rebar fabrication yard	RFY	0	0	0	0	0	0	0	0	0	1000	0	1000	0	-1000	0	0	1000	0	0	0	1000	-1000	1000	0	0	0
Toilet on site	WC	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	0	0	-100	0	0	0
Welding shops	WSh	0	0	0	0	0	0	0	0	0	0	0	0	0	-1000	0	0	0	0	1000	0	0	-1000	1000	0	0	0
SubContractor Site office	SOFF	0	0	0	1000	0	0	0	1000	-1000	-100	-100	-1000	-100	1000	0	0	-100	1000	-1000	0	-1000	0	0	0	1000	0
First aid	FA	0	0	0	0	0	0	0	0	100	100	100	0	0	100	0	1000	0	0	1000	-100	1000	0	0	0	0	0
Machine room	MR	0	0	0	0	0	0	0	0	0	0	0	0	-100	0	0	0	0	0	0	0	0	0	0	0	100	0
Tank	T	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	1000	0	100	0	0
Sampling lab	SL	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 3 Developed proximity matrix

4.3 Results Analysis

A number of trials were carried out with the aim of minimizing the objective function of the model, with the runtime used as a stoppage criteria for the algorithm. Additionally, the solution that was obtained from the reference paper was also fed to the model in order to measure the fitness of the proposed solution for comparison purposes. Table 4 shows a summary of the optimization results obtained from the final run as well as the reference paper solution compared to the model's solution in Fig. 4. There is a substantial improvement in the model's results compared to that of literature. The model's score reached almost 10% of the literature value indicating a major change. The model runtime is also improved; the explanation to that is the simplicity of shape definition in the developed model which reduced the computational time significantly.

Table 4 Comparison between reference model and model developed

Comparison aspect	Developed model	Literature result (Elbeltagi)
Constraints achieved	Yes	Yes
Fitness score	70,765	764,568

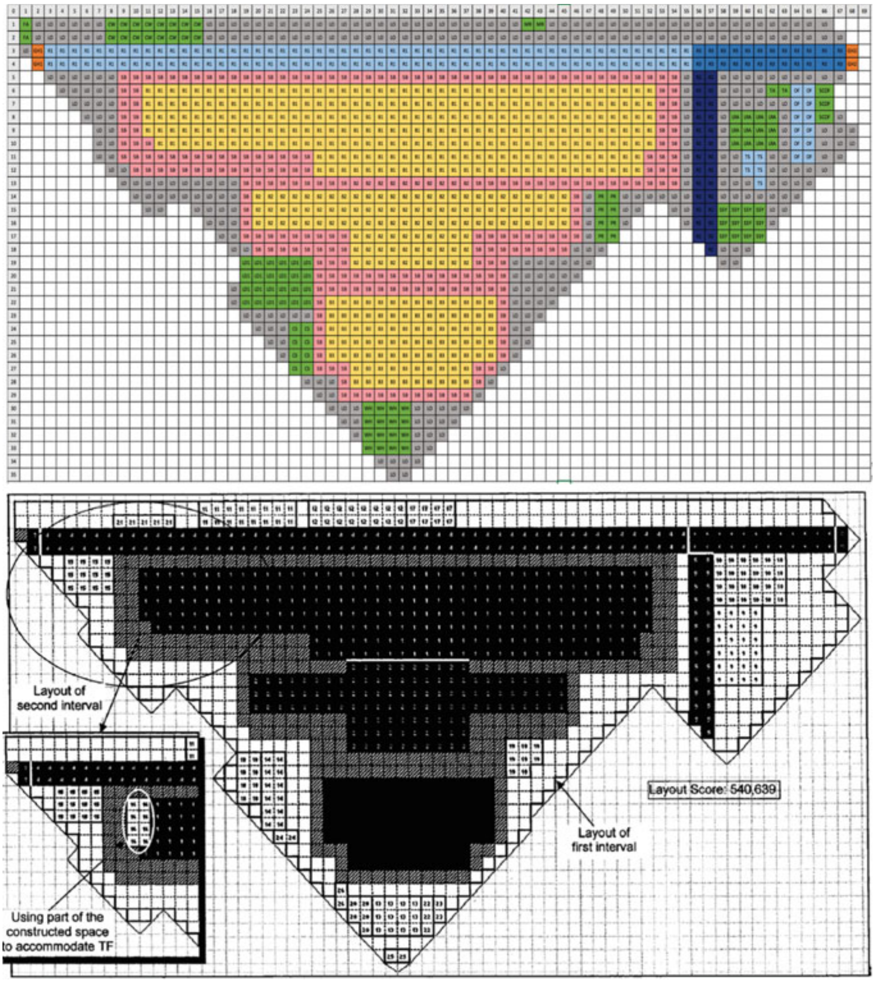


Fig. 4 Developed model's optimized solution (top), Elbeltagi's optimized solution (bottom)

5 Conclusion

From all of what was discussed, it can be concluded with confidence that the developed model is successful in optimizing site layout and shows improvement over that of the reference model. The shape definition technique developed in the paper is simple and effective in capturing the irregularities of facilities and can be modified in its accuracy based on the mesh unit size. Safety elements were considered in the planning of site layout through constructing safety zones and in the consideration of the proximity matrix. However, there is still room for improvement in the proposed model, the model is far from reaching its full potential. There is room to improve the model's flexibility and ease of application. Linking the model to AutoCAD or other drawing software and developing a code to analyze drawings to detect the shape definitions parameters is considered the most useful expansion for the model.

References

1. Abotaleb I, Nassar K, Hosny O (2016) Layout optimization of construction site facilities with dynamic freeform geometric representations. Autom Constr 66:15–28
2. Elbeltagi E et al (2004) Dynamic layout of construction temporary facilities considering safety. J Constr Eng Manag 130(4):534–541. https://doi.org/10.1061/(asce)0733-9364(2004)130:4(534)
3. Farmakis PM (2018) Genetic algorithm optimization for dynamic construction site layout planning. Organ Technol Manag Constr Int J 10(1):1655–1664
4. Xu J, Liu Q, Lei X (2016) A fuzzy multi-objective model and application for the discrete dynamic temporary facilities location planning problem. J Civ Eng Manag 22(3):357–372