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Dynamic site layout planning through minimization of total potential energy

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ABSTRACT

Dynamic site layout planning is the task of determining the overall optimum location of objects such as temporary facilities, storage areas, and workshops on the construction site. This paper presents an innovative dynamic model that is able to generate layouts that are optimized over the duration of the project. The model applies energy principles governing a physical system to search for the optimum location of objects. In this model, objects with more impact on the layout are able to obtain and reserve their optimum locations even if they arrive to the construction site in later stages. The model allocates space to objects only for the duration they are required on the site, and accordingly, it enables a realistic representation of space availability on the site and allows the reuse of space over the time. A numerical example is presented to demonstrate the capability of the developed model.

1. Introduction

Site space is considered a limited resource in construction projects [1]. Different objects such as temporary facilities (e.g. batch plant), major equipment (e.g. tower crane), material storage areas (e.g. gravel storage), and working areas (e.g. rebar cutting area) exist on a site to support construction activities. These objects arrive to the site at different points of time and occupy space on the site for different durations. In a construction site, resources (material, labor and equipment) travel between objects to perform or support different activities. For instance, gravel is taken from its depot area to the batch plant; or the concrete is transferred from the batch plant to the structures under construction. There is a cost associated with the resource exchange between objects which depends on the workflow and distance between objects. Locating objects close to each other can minimize this cost. On the other hand, safety related issues may occur when certain objects are located too close to each other. For instance, a welding shop should be located far from a storage area for flammable material to prevent safety hazards. In current practice, site layout objects are often located in the best available space on a first-come first-served basis. This can lead to decreased safety and productivity, or impose unnecessary relocation costs on the project. Determining the optimum location of objects on the construction site before the commencement of construction, in order to minimize different travel distances and maximize safety and productivity, is referred to as site layout planning. An efficient site layout can have a significant impact on the productivity, cost, and safety on construction sites [2].

Inspired by the research on *plant layout*, construction site planning has received the attention of researchers and industry practitioners in the past three decades [3]. Several models have been developed to automate the site planning procedure in order to generate optimum layouts for construction sites [4–18]. The main challenge in developing optimized layouts is in reflecting the dynamic nature of the site over the course of a construction project. Construction activities change as the project progresses, and accordingly, the number and nature of associated objects are subject to change as well. Site layout objects enter the site at different times, occupy space on the site for different periods of time, and leave the site when they are no longer required (e.g. equipment) or get installed in the structure (e.g. materials). Developing layouts that are optimized over the duration of the construction project is referred to as *dynamic* site layout planning.

In order to generate dynamic layouts, planning models need to take into account the changes in space requirements over the course of the project. Some of the previous studies have proposed dividing the project duration into several time intervals to represent these changes, and to generate a separate partial layout for each interval [6,14,15]. However, combining separately optimized partial layouts does not necessarily lead to a layout that is optimized for the entire duration of the project [13]. In an actual dynamic site layout model, the changes on the construction site will have to be incorporated into the model. Reflecting the actual duration of objects in the optimization process will make dynamic site planning computationally challenging, which could be the reason why it has not been addressed in the literature until now. This paper presents an innovative approach based on physics principles that, for the first time, considers the actual duration of objects on the site, and generates dynamic layouts that are optimized over the duration of the project.

2. A comparative overview of site layout models

The role of objects on the construction site is to provide support for construction activities. An efficient site layout allocates locations to

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objects where they can better support the activities. The time and duration for which the objects are required on the site depends on the activities they are associated with. Depending on the type of project delivery, these objects can arrive to the site several days to several months prior to the activities they support. Nonetheless, the space usage on the site changes over the course of construction. As the project progresses, the required objects, and accordingly the space required to accommodate them on the site, are subject to change. It is important to incorporate these changes in the site plan in order to reach layouts that are realistic and make optimum use of the space on the site. The impact of temporal changes in space requirements on the final outcome in dynamic site layout planning can be illustrated through the following example. Consider a construction project with nine (9) objects that are required on the site for different times and durations as shown in Fig. 1. As can be inferred from the schedule, only two objects, Geotechnical Lab (Object 1) and Offices (Object 4), are required in the first two months of the project. The end of each bar in the schedule denotes when the object is no longer required on the site, and hence, when its space becomes available for the arriving objects. For example, the Geotechnical Lab. (Object 1) is no longer required after four months, and therefore its space is available to locate the Batch Plant (Object 3) or the Gravel Depot (Object 7).

Existing studies have taken different approaches to reflect such changes in site layout planning. *Static* models ignore the changes that occur on construction sites over the course of time. These models assume that all objects exist on the site for the entire duration of the project [4,5,8,9,12,16,19–25]. Static models can be suitable for projects with short durations and large construction sites, where space is abundant, and there are not many changes in the layout of the construction site over the course of time. However, they are not practical for more complex projects with longer durations where numerous objects arrive and leave the site over the course of construction. Static models do not allow reusing the space occupied by objects which are no longer required on the site. For instance in the above example, the Geotechnical Lab. (Object 1) and the Brick Depot (Object 8) would not be allowed to use the same space in a static model, even though in reality they do not exist on the site at the same time.

To overcome this limitation, and to reflect changes in space requirements over time, some models divide the project duration into several discrete time intervals and generate an optimized partial layout for each time interval [1,6,7,13–15,26–28]. These models allow reusing space that was vacated during one time interval, in its succeeding time interval. For instance, assume that the duration of the project in the previous example is divided into two time intervals (Fig. 1): from month 1 to 10 and from month 11 to 18. Objects entering the site in the second partial layout (i.e. Carpentry Shop (Object 5), Brick Depot (Object 8), and Landscape Shop (Object 9)) are able to reuse the space of objects which are no longer required in this interval, namely: Geotechnical Lab. (Object 1), Rebar Shop (Object2), and Gravel Depot (Object 7). This *phased* approach constitutes an improvement over static models, in that it represents some of the changes in site space requirements. Compared to *static* models, *phased* models provide a better opportunity for objects to obtain optimum locations, since fewer objects compete for the same space on the site. For example in the aforementioned *phased* scenario, six objects will be competing in each partial layout for the best locations on the site, whereas in the *static* scenario nine (9) objects were competing with each other. In addition, in *phased* models the representation of space requirements and space availability on the site are closer to the reality of construction sites. As a result, it could be expected that the layout generated by phased models are closer to a layout that is optimized over the entire duration of a construction project.

Despite the above-mentioned advantage, in *phased* models partial layouts are often optimized separately. It is important to note that a set of individually optimized partial layouts does not necessarily provide a site layout that is optimized for the overall duration of the construction project [29]. In addition, the time intervals in phased models are usually optimized in chronological order [6,15]. Therefore, the location of objects in later time intervals (e.g. Carpentry Shop and Bricks Depot in Fig. 1) is highly influenced by those in earlier ones (e.g. Batch Plant, Offices, and Tower Crane). This approach will not be effective for cases where more important objects arrive to the site in later phases of the project.

The other disadvantage of *phased* layouts is that although space can be reused from one partial layout to another, within each partial layout, space reuse is not allowed [10]. For example, using the *phased* approach, Gravel Depot (Object 7) cannot take the space of Geotechnical lab (Object 1) in the example above, even though the latter is not on the site anymore. This will reduce the efficiency of the generated layouts compared to a layout that considers the actual duration of objects on the site. For instance, in Fig. 1, no more than four (4) objects are required on the site at any given time, while in a *phased* model six (6) objects will be competing over optimum positions in each partial layout. This is due to the fact that objects are assumed to be present on the site for the duration of the time intervals. As a result, their chances in getting the desired locations decrease. A detailed overview of different approaches for the modeling of the time factor in construction site layouts can be found in [29].

The model presented in this paper considers time as a continuous quantity and assigns space to objects for the exact duration they are required to be present on the site. As a result, the developed model provides a realistic representation of the space requirements and availability on the site during the project. As will be discussed, this is an important attribute which enables the developed model to generate layouts that are optimized over the duration of the project, while considering the *dynamic* changes on the site.

3. Minimum total potential energy for site layout planning

Minimum Total Potential Energy (MTPE) is a physics principle that has been extensively used to solve engineering problems such as determining deflections of structure under external loads in elasticity problems [30]. According to the MTPE principle, in a physical system

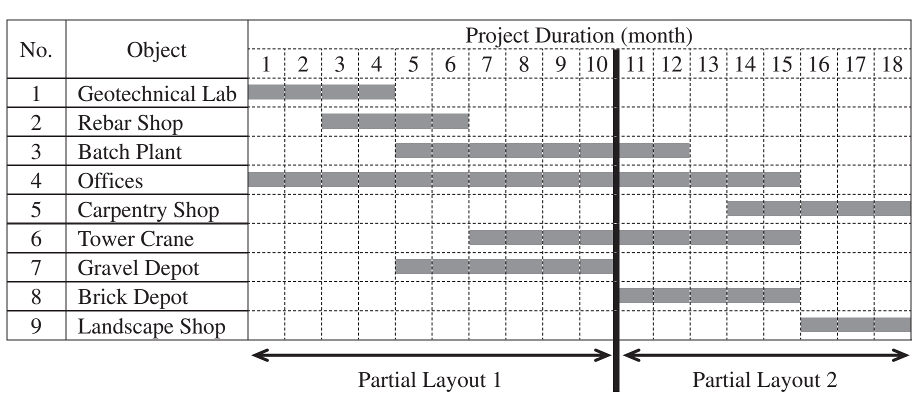

Fig. 1. Space requirement for 9 site layout objects over the course of a project.

composed of particles, the total potential energy is defined by the internal forces and the distances between particles [31]. For instance, the potential energy of a system composed of a ball and the earth depends on the weight of the ball (internal force) and the height of its center point from the earth (distance). The total Potential Energy of a system of particles is presented as:

$$PE = \sum F_{ij} d_{ij} \tag{1}$$

where F_{ij} represents the pulling/pushing force between particle i and j, and d_{ij} denotes the distance between the two particles. According to the law of conservation of energy, the total energy of a system with internal forces (i.e. potential energy + kinetic energy), remains constant at all times [32]. The internal forces between particles cause them to move and gain kinetic energy. This means that part of the Potential Energy (Eq. (1)) of the system is converted into the kinetic energy. If for any reason, the particles lose their kinetic energy (for instance when the kinetic energy is converted to heat due to friction), the lost kinetic energy will not transform back to potential energy. Consequently, the potential energy of the system will decrease continuously until all objects reach the equilibrium state where internal forces are balanced and particles get stable in their positions. Based on the Minimum Total Potential Energy (MTPE) principle, the configuration of particles in this equilibrium state has the lowest possible potential energy [32,33].

Site layout planning involves optimization of the location of numerous objects that have different (and at times, opposing) relationships and various temporal and special dimensions. The main challenge in the optimization of dynamic site layouts lies in modeling the changes that occur in the object requirements and their interrelationships throughout the course of the construction project. Due to its similarity in concept and composing components (objects and particles, relationship and forces, site boundary and physical system), this research explored the possibility of using MTPE principles to generate site layouts that are optimized over the project duration, considering the dynamic changes on the site. MTPE appeared to provide the capability of searching for numerous objects with changing relationships at the same time. Therefore, the hypothesis of this study was that MTPE principles can be used in developing dynamic site layouts.

In order to apply the MTPE principle to dynamic site layout planning, the *layout* can be viewed as a *physical system* in which the *objects* are presented as *particles* and the *relationships* between objects (i.e. how close or far they should be from each other) are reflected as the *internal forces* between particles. In a physical system, the particles move based on the internal forces that act on them, until they reach the equilibrium, where the system has the lowest Total Potential Energy. With the same token, the relationships among objects in a site layout act similar to forces on particles in a physical system, and cause the objects to move and search for a position where their forces are balanced. As will be discussed in Section 4.3, the arrangement of the objects on the site at this equilibrium state represents the optimum locations for objects on the site.

4. A dynamic model for site layout planning

Overview: In the dynamic site layout planning model presented here, the search process starts from an initial random distribution of *all* the project objects, regardless of the time they are required on the site (e.g. all nine objects in Fig. 1). Using Minimum Total Potential Energy (MTPE) principle, the initial locations of all objects will change simultaneously based on the closeness relationships defined between them. The existing duration for which objects are required on the site is incorporated in their definition. As a result, although all objects engage in the search simultaneously, objects compete for space only for the durations they exist on the site. Engaging all the objects in the search process simultaneously provides the objects that are required later in the project (e.g. Carpentry Shop (Object 5) in Fig. 1) an equal chance to compete over desired locations with objects that are required earlier on (e.g. Offices (Object 4)), and with which they have a time overlap. Objects with stronger relationships, which have higher influence on the overall fitness of the layout, will get the desired locations regardless of their time of arrival to the site in the course of construction, and their initial locations in the search. This means that the location of objects in the layout is optimized considering object requirements and object relationships for the entire duration of the project. The following sections describe different aspects of the developed model in detail.

4.1. Construction site representation

A common practice used in previous studies for modeling the site space is to reflect the available space as a set of discrete cells using an orthogonal grid, and allowing objects to be located only in the grid cells (e.g. [5,13,19,23,25]). The use of grids simplifies the search

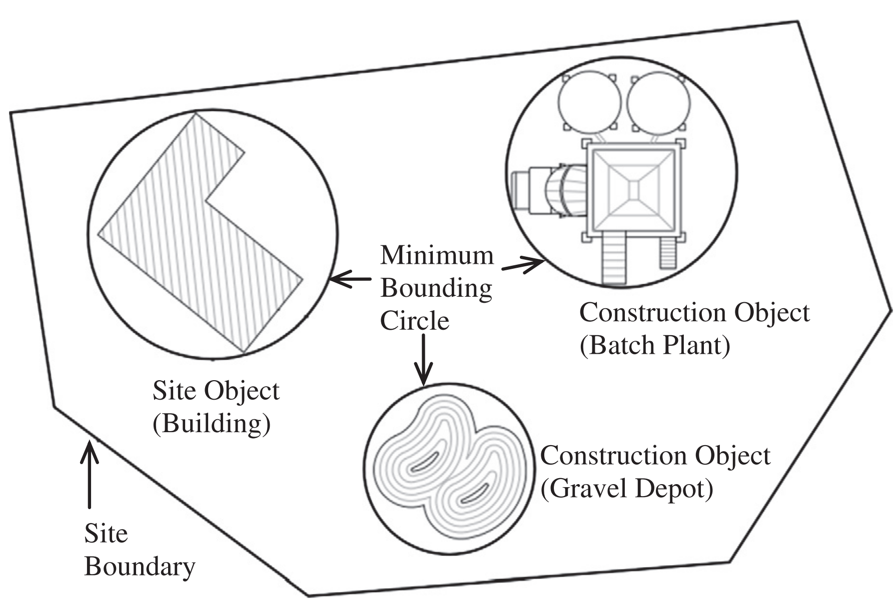

Fig. 2. Object and site representation in the developed dynamic site layout model.

procedure by decreasing the number of possible choices for the position of objects. In addition, in this approach the shape of the site is restricted by the orthogonal gridlines. In reality, the construction site can take any shape and the objects can be located in any available space on the site. The model developed in this study represents the site space as a continuous quantity and allows the objects to be located anywhere in the construction site. During the search for optimum locations, objects search freely in the continuous space (as opposed to discrete search in a grid system) and as the model reaches the equilibrium, they can take position anywhere in the continuous space of the site. This increases the possible choices for locating objects and causes the model to be closer to the reality of construction projects. In addition, the developed model is capable of analyzing any irregular site shapes in the search process (Fig. 2). An accurate representation of the construction site is important for site layout modeling, as it enables the development of more realistic and efficient layouts.

4.2. Object representation

Objects involved in the site layout are represented by their minimum bounding circles to facilitate the search and optimization process (Fig. 2). In the model, objects are divided into two groups based on the way they are engaged in the search process: *site objects* and *construction objects*. *Site objects* are those that have a known location on the site, and that do not require to be positioned in the search process. Examples of site objects are buildings that are under construction, or an existing structure on the site. They could also be objects that support construction activities, but a specific location has been allocated for them. Although the position of these objects will not be determined in the search process, they will affect the distribution of the other objects, and hence they play an important role in the search. *Construction objects* are those whose location will be determined in the process of site layout planning [27]. Examples for these objects include site offices, material depots, working areas, and batch plants.

Both object types can exist on the site for a limited time or for the entire duration of the project. The duration for which objects exist on the site is embodied in the objects (i.e. incorporated as an attributes for the object class definition). Therefore, unlike static and phased models, in the developed model objects compete for best locations only for the duration they exist on the site. As a result, the model allows the space that is occupied by an object to be reused by other objects before and after the object's existence on the site. This enables the model to take into account the changes on the site over the course of construction in the search process and enable the development of dynamic site layouts.

4.3. Objective function

The objective of the model is to optimize the distance between objects, in order to decrease travel and material handling time, and increase safety on the site. Since the location of the *site* objects is known, the fitness of the generated layout depends solely on how well the *construction* objects are positioned on the available site space. The fitness of a site layout is measured by the following objective function:

$$OF = \sum W_{ij} d_{ij} \tag{2}$$

where W_{ij} is the closeness weight defined between objects i and j, and d_{ij} is the distance between objects i and j. To decrease the cost of workflow and increase safety on the site, the model has to *minimize* this objective function. Positive or negative closeness weights can be assigned to pairs of objects to represent how close or how far they are desired to be located from one another. Positive closeness weights can be defined based on the actual frequency and cost of the resource exchange or workflow between two objects (e.g. the cost of moving gravel to the batch plant for each trip). Since it is difficult to determine the exact frequency and costs of workflows between objects at the planning stages of the project, they are often represented by relative closeness weights in site layout models (e.g. [5–7,12,15,25]); a relatively large closeness weight between two objects indicates a significant workflow, and minimizing the objective function will lead the objects to be located close to each other. Negative closeness weights, on the other hand, are used to represent that two objects are desired to be located far from each other, for example, due to safety related issues. For instance, a negative closeness weight can be assigned between the welding shop and the storage area for flammable material to show that these two objects have to be located as far from each other as possible. Minimizing the objective function will lead two objects with negative closeness weight to be located far from each other. Therefore, by minimizing the objective function based on the closeness weights defined between pairs of objects, the model decreases the travel costs and increases the safety on the construction site.

4.4. Methodology: optimizing site layout through minimization of total potential energy

The model developed in this research uses the MTPE principle described in Section 3, to generate site layouts that are optimized over the course of construction project. In this approach, the *site layout* is embodied as a *physical system* in which the *objects* represent the *particles* and the *closeness weights* between objects (i.e. how close or far they should be from each other) represent the *internal forces* acting on particles. As a result, the Objective Function of the layout as defined in Eq. (2), will be the same as the Total Potential Energy of the physical system (Eq. (1)). When searching for the optimum locations, objects (particles) move due to their closeness weights with other objects (internal forces between particles) and search for balance in their forces. As objects on the site start to move based on the defined closeness weights between them, the Objective Function (total potential energy) of the layout (physical system) decreases until all objects (particles) reach the equilibrium state. Just as in a physical system, in the equilibrium state, the Objective Function of the layout (total potential energy of system) is at its minimum value. In other words, the arrangement of objects on the site at the equilibrium state yields the minimum value for the Objective Function (OF) for the layout, and therefore, represents the optimum locations for objects in the site layout. Using the MTPE to search for the optimum solution is similar to Simulated Annealing (SA) optimization in that an initial solution is modified based on energy changes at every step of the solution [34]. The important difference here is that in SA the changes are made randomly, whereas, as will be explained, in the MTPE the internal forces always directs the object towards the equilibrium state with the lowest potential energy.

During the search, objects compete for spaces only for the actual duration of their existence on the site and considering their relationships with objects with which they have time overlaps. As a result, the site layout is optimized considering the actual changes of object requirements and relationships over the course of the project, and hence, the generated layout is dynamic. The details of incorporating the time-related considerations into the model (i.e. dynamic aspects) are explained in Section 7.

5. Searching for the optimum layout using MTPE

The search for optimum layouts starts from a random distribution of construction objects on the site. Based on the closeness weights defined for pairs of objects, and using the MTPE principle, construction objects start to move in search for the optimum layout until they reach the equilibrium state. To illustrate the search process, consider a site with one construction object (O_1) and three site objects (O_2, O_3, and O_4) in an initial random layout shown in Fig. 3a. The construction object (O_1) has the following closeness weights with the three site objects, respectively: $W_{1-2}=60$, $W_{1-3}=50$, and $W_{1-4}=-70$. Each closeness weight represents two equal forces, in opposite direction, that act on the two engaging objects. For example W_{1-2} is reflected by F_{1-2} and F_{2-1} acting on O_1 and O_2. The positive closeness weights (W_{1-2} and W_{1-3}) represent pulling forces between objects, and the negative weight (W_{1-4}) represents pushing forces. Site objects (O_2, O_3, and O_4) remain stationary in their position while the forces cause the construction object (O_1) to move in the direction of its resultant force (R) (see Fig. 3). The resultant force (R) is the vector summation of all forces acting on the object and directing it toward the equilibrium state:

$$R_x = \sum F_x \qquad R_y = \sum F_y. \tag{3}$$

Using the xy coordinates of the three objects as indicated in Fig. 3, and the defined closeness weights, the resultant force (R) for O_1 can be calculated as:

$$R_x = F_{1\text{-}2}\,\mathrm{Cos}(77) - F_{1\text{-}3}\,\mathrm{Sin}(67) - F_{1\text{-}4}\,\mathrm{Sin}(75)$$
$$R_x = -100.1$$
$$R_y = F_{1\text{-}2}\,\mathrm{Sin}(77) - F_{1\text{-}3}\,\mathrm{Cos}(67) + F_{1\text{-}4}\,\mathrm{Cos}(75)$$
$$R_y = 57.0$$

and therefore,

$$R = 115.2 > 30°.$$

When construction object (O_1) moves, the closeness weights and the *magnitude* of their respective internal forces remain constant. However, changes in the location of the construction object will cause the *direction* of the internal forces, and accordingly, the magnitude and direction of the resultant force (R) to change at every moment of this movement. O_1 will continue to move in the direction of its resultant force until it reaches the equilibrium state (Fig. 3b). In this state all forces acting on O_1 are balanced, and accordingly, the object no longer moves:

$$\sum F_x = F_{1\text{-}2}\,\mathrm{Sin}(66) + F_{1\text{-}3}\,\mathrm{Cos}(77) - F_{1\text{-}4}\,\mathrm{Cos}(20)$$
$$\sum F_x = 0 \quad \text{and}$$
$$\sum F_y = F_{1\text{-}2}\,\mathrm{Cos}(66) - F_{1\text{-}3}\,\mathrm{Sin}(77) + F_{1\text{-}4}\,\mathrm{Sin}(20)$$
$$\sum F_y = 0.$$

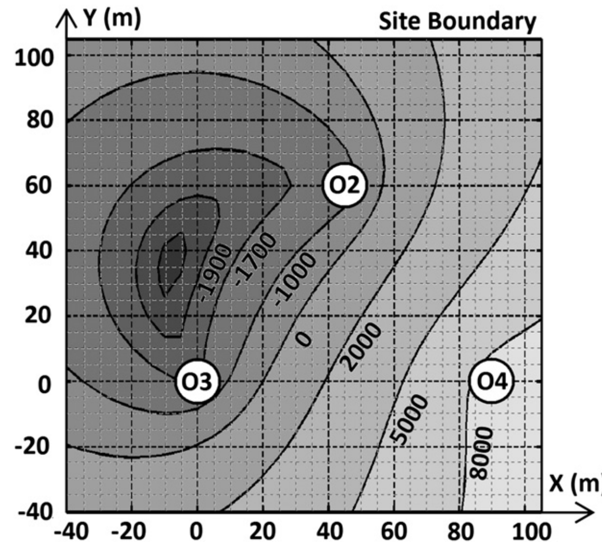

Fig. 4. Objective function for all possible locations of the construction object (O1) on the 5 m interval grid.

As explained, according to the MTPE principle the equilibrium state represents the minimum total weighted distance for the layout. In other words, it represents the optimum location for objects, where the Objective Function of the layout is at its minimum possible value.

To validate the proposed methodology, the above example was solved in an exhaustive mathematical search. The objective function (OF) of the layout was calculated for various possible locations for the construction object (O_1) on the site on a grid with 5 m intervals (784 locations). Fig. 4 shows the resulting topography of the Objective Function generated using Matlab. As can be inferred from Fig. 4, the objective function decreases as O_1 is positioned in locations that are closer to [−8, 36], which is the location identified by the MTPE methodology (see Fig. 3). When O_1 is located in this position, the objective function gets the minimum value of −1973. Therefore, the MTPE method was able to find the most optimum location for the object.

It should be noted that in a physical system, the total potential energy cannot get below zero. However, in this model, the negative closeness weights (used to indicate repellence between two objects) can cause the objective function to take negative values. Nonetheless,

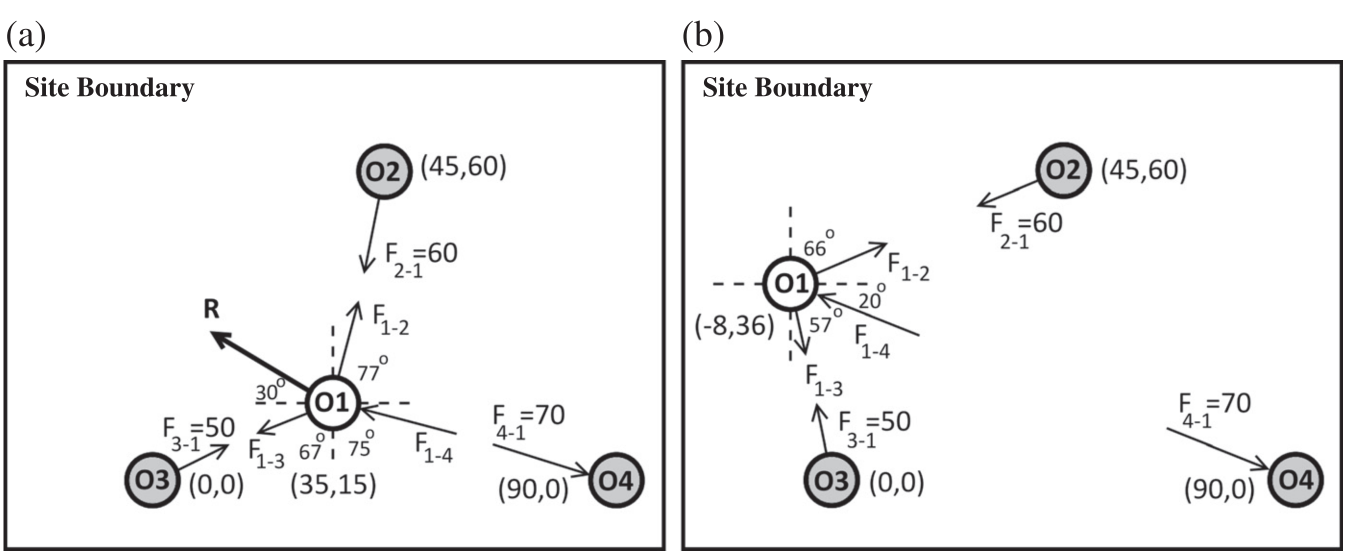

Fig. 3. Forces acting on a construction object: a. moving state, and b. equilibrium state (optimum layout).

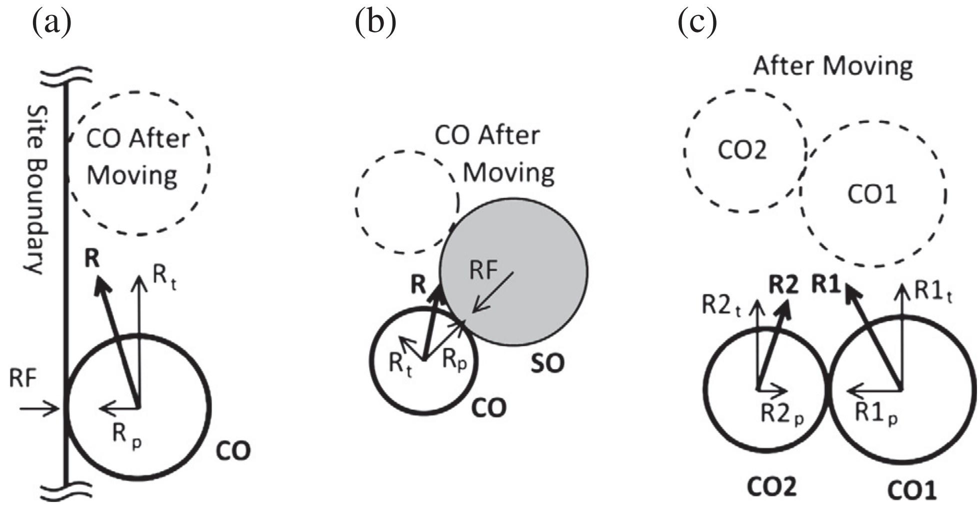

Fig. 5. Possible types of object clashes: a. Construction Object-Site Boundary, b. Construction Object-Site Object and c. Construction Object-Construction Object.

the layout with the minimum OF represents the most optimum layout for the defined relationships.

The velocity of objects is ignored in the search process of the model (i.e., $v = 0$) due to the following reasons:

1) Since the forces acting on objects are balanced in the equilibrium state, the objects will keep moving if they have a velocity when they reach this state, and pass the equilibrium point. Ignoring the velocity will result in objects becoming stable when they reach the equilibrium state.
2) When the velocity is ignored ($v = 0$), the objects will not gain momentum ($mv = 0$), and will therefore not bounce when they clash with site boundaries or other objects. Instead, they will keep moving in the direction of their resultant force, which will lead them to the balanced position in the equilibrium state (see Section 6 for a discussion of Object Clashes).
3) Assuming that the velocity is zero means that the kinetic energy of the system is zero at any moment ($1/2mv^2 = 0$), and therefore, it cannot transfer back to potential energy. The potential energy will thus decrease continuously as the objects move in search of their optimum location. This enables the model to find the configuration of objects on the site that has the lowest potential energy, or in other words, the layout with the minimum objective function (OF).

In the developed model, objects constantly change position in the direction of their resultant force without gaining velocity. When the objects reach their position in the equilibrium state, where the resultant forces of all the objects are zero, they will stop moving and become stable. At this state, the objective function is minimized and the optimum layout is generated.

6. Dynamics of object clashes

Construction objects can clash with site boundaries or with other objects (construction objects or site objects) as they search for their optimum locations. This section explains how clashes can impact the resultant force, and accordingly the direction that objects are moving in. When a construction object clashes with the site boundary or with a site object (Fig. 5a and b), they will return a *reaction* force (RF) towards the construction object, since the site boundary and the site object are stationary. This force will change the resultant force and the direction of movement of the construction object. The reaction force (RF) will be equal to the perpendicular component of the resultant force (R_p) in magnitude but in the opposite direction ($|RF| = |R_p|$). As it is an acting force on the construction object, the reaction force (RF) cancels the perpendicular component (R_p) and causes the object to move in the direction of the remaining tangent

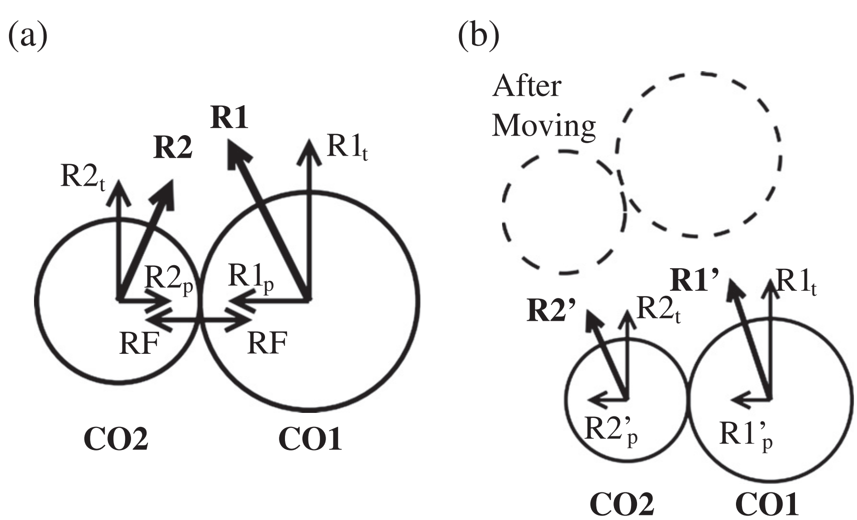

Fig. 6. Forces of two construction objects as they clash: a. Reaction Forces (RF) and resultant forces (R) at the clash and b. new resultant forces (R) after the clash.

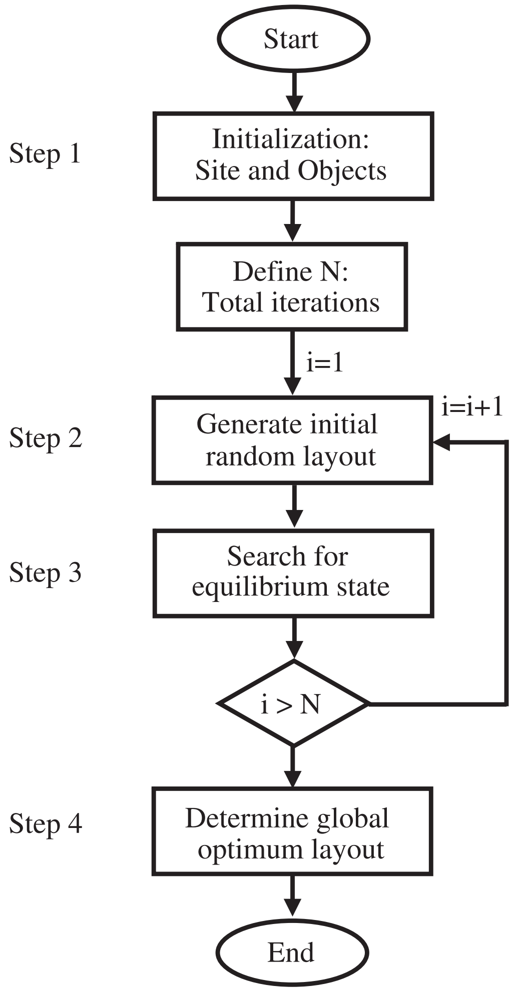

Fig. 7. The search algorithm in the developed dynamic site layout model.

force (R_t). Therefore, the construction object will either move along the site boundary (Fig. 5a), or slide around the fixed object (Fig. 5b), as relevant to the case.

Construction objects that have time overlaps can clash with one another during the search process. If the two objects that meet in the same space do not have time overlaps, they will simply pass through each other (or reside over the other) since they are not competing for the space at the same time. When two construction objects that have a time overlap clash, they will push each other as they attempt to move in their respective previous directions (Figs. 5c and 6). Based on the Newton's third law, the objects will exert two reaction forces (RF) on each other, which are equal in magnitude but in opposite directions (Fig. 6a). These forces will change the magnitude and the direction of the resultant forces of the two construction objects (R1 and R2 in Fig. 6a). In the new state (Fig. 6b), the perpendicular components of the new resultant forces ($R1_p'$ and $R2_p'$) are equal. The magnitude of the reaction force (RF) between two clashing construction objects can be calculated as:

$$\begin{aligned}
&\left|R1_p'\right| = \left|R2_p'\right| \\
&\left|R1_p\right| - |RF| = |RF| - \left|R2_p\right| \\
&|RF| = \left(\left|R1_p\right| + \left|R2_p\right|\right)/2.
\end{aligned}$$

Eventually, the object with larger resultant forces (R) – e.g. PO1 in Fig. 6 – will push the other object and will move towards its desired position. As a result, objects with higher closeness weights (larger forces), which have a higher impact on the fitness of the layout, are able to claim and get their desired near-optimum locations regardless of their initial location in the search or the time of arrival on the site. This is a significant feature which, as will be explained later, enables the developed model to reach layouts that are optimum over time from a randomly generated initial layout.

7. Dynamic site layout planning

Dynamic site layout modeling refers to the process of generating layouts that are optimum for the duration of the construction project, while considering the actual duration for which the objects are required. To enable dynamic site layout planning in the present model, all the construction objects, regardless of when they will actually be required to be on the site, will start searching for their optimum locations, simultaneously. The objects are modeled as smart objects; i.e. the information regarding the time they are required on the site and their closeness weights with other objects are embedded in them as object attributes. Objects that do not have time overlap with each other can pass over one another or even occupy the same space. This means that the space occupied by one object can be reused by other objects in earlier or later periods of time. Objects with time overlaps cannot pass over each other, nor can they occupy the same space. When objects with time overlaps reach each other, a "clash" occurs.

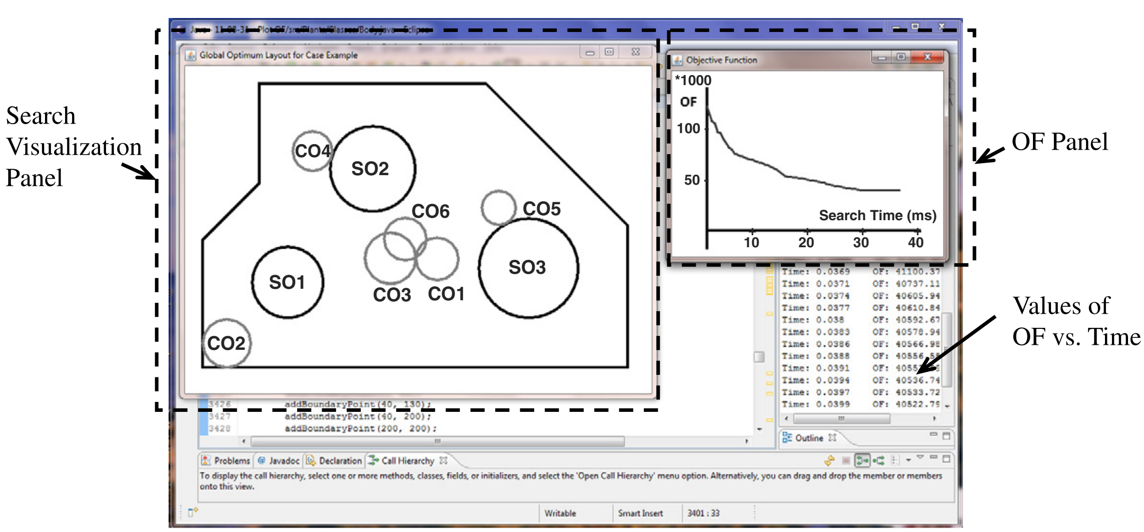

Fig. 8. Snap shot of the developed tool.

Table 1
Site and construction object information.

Object	Name	Size (radius)(m)	Position (center)	Object schedule (months)									
				1	2	3	4	5	6	7	8	9	10
SO1	Parking bldg – concrete structure	25	(60, 60)										
SO2	Shopping mall – steel structure	30	(120, 140)										
SO3	Theatre hall – concrete structure	35	(230, 70)										
CO1	Rebar workshop	15	–										
CO2	Material storage	17	–										
CO3	Batch plant	18	–										
CO4	Carpentry shop	14	–										
CO5	Electrical tools storage	12	–										
CO6	Security office	15	–										

As explained in the previous section, clashing objects will push each other in an attempt to continue moving in their previous direction, or to compete over a desired position. When a clash occurs, objects with stronger forces (larger closeness weights) will be able to push other objects and stop in their desired position. This means that in the developed methodology objects with higher closeness weights, which have more impact on the fitness of the layout, can get their desired location regardless of their position in the initial layout or the time period they are required on the site. MTPE method allows objects to search in the continuous site space (as opposed to predetermined locations or grid cells) and take their final position anywhere on the site — just similar to how objects can be located anywhere in an actual construction site. As all objects move in search for their optimum position, the objective function keeps decreasing, until it reaches its minimum value. That is when the objects reach the equilibrium state and the optimum site layout has been generated.

8. Model development and implementation

Using the principles explained in the previous sections, a dynamic site layout model has been developed. The search process for the optimum site layout is carried out in the following stages (Fig. 7):

1 *Initialization*: In the first step of the search process, the site boundary and objects are defined in the model. Site boundary is defined by indicating the coordinates of its vertices. As for the objects, the model requires the size and schedule of the objects (i.e. time of arrival to and departure from the site). It also prompts for the location of *site* objects. Once the objects are defined, the closeness relationships with other objects and their weights can be indicated. This information will be embedded in the objects and will be used in the search process.
2 *Generate random initial layout*: The initial layout is generated by locating the *site* objects in their predefined locations. All *construction* objects, regardless of their schedule, will be randomly distributed on the site. Random [x, y] coordinates within the site boundary are generated to define the position of the construction objects in the initial layout. Random positions for construction objects are generated one at a time. Object overlap is not allowed in the initial layout. If overlaps occur in positioning a construction object, new random coordinates will be generated.
3 *Search for the equilibrium state*: Once the initial random layout is established, all construction objects will start searching for their optimum positions simultaneously, by moving in the direction of their respective resultant forces (R). As objects are smart in this model, they *know* which objects they can overlap with and what the magnitude and direction of their resultant force is at any given time during the search process. The value of the objective function gets recorded as the construction objects move in search of their optimum position. The search ends when objects reach the equilibrium state; i.e. when no change in the OF value is observed. In this state, objects have reached their minimum potential energy and the locations of objects represent the optimum layout for the site. The final layout will be saved to be compared to those generated from different initial layouts.
4 *Determining the global optimum layout*: The procedure of generating random initial layouts and determining final layouts is repeated several times to ensure that the search process does not get trapped in local optimums. All generated layouts will be compared to determine the global optimum layout.

Table 2
Closeness weights between objects.

Object	CO1	CO2	CO3	CO4	CO5	CO6
SO1	120	−60	130	0	−70	150
SO2	40	−80	40	90	50	100
SO3	140	−140	135	−40	120	180
CO1	–	0	0	0	0	0
CO2	–	–	0	15	0	10
CO3	–	–	–	0	0	0
CO4	–	–	–	–	8	0
CO5	–	–	–	–	–	20
CO6	–	–	–	–	–	–

A prototype of the model has been developed using java programming language. Fig. 8 shows a snapshot of the developed tool and its main panels. The "Search Visualization Panel" visualizes the search process as the objects move in search for the equilibrium state, and the "Objective Function" (OF) Panel shows the changes in the objective function in real-time throughout the search process.

9. Numerical example

An example of a construction project is used to evaluate the performance of the model and demonstrate its capabilities. The project includes three (3) site objects (SO1, SO2, and SO3) and six (6) construction objects (CO1 to CO6). The properties of these nine objects

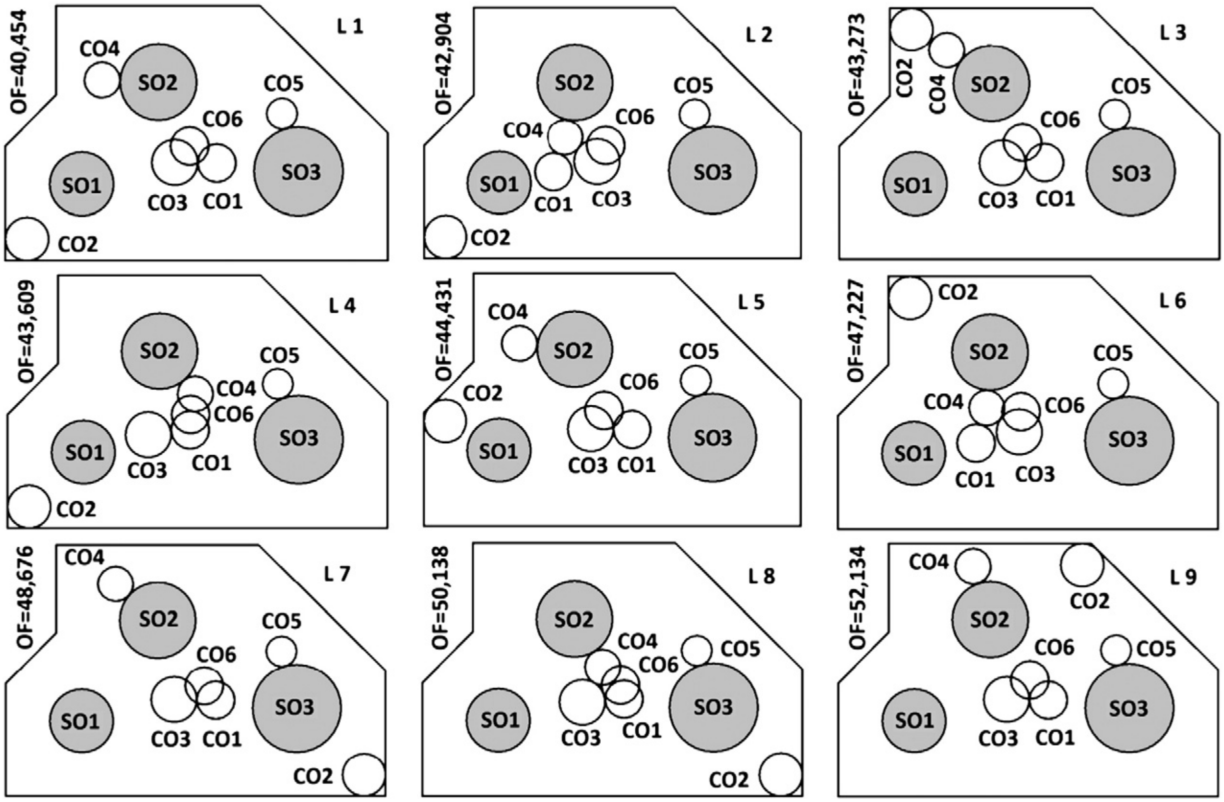

Fig. 9. The resulting nine (9) equilibrium states for the example.

are presented in Table 1. The total duration of the project is 10 months and the schedule of the objects (i.e. the time they are required on the site) is depicted at the right side of Table 1. The desired closeness weights between the objects are presented in Table 2. Positive closeness weights between two objects indicate that objects are preferred to be located close to one another, while negative values show that object need to be located far from each other.

The example was tested in 1000 runs to study the difference between the final layouts generated from different initial layouts. It took the model 31 s to reach the equilibrium state for all 1000 runs altogether. A personal computer with 2 GHz Core 2Duo CPU, 3 MB cache memory, and 3 GB of RAM was used in this experiment. 149 out of 1000 runs (15%) did not reach equilibrium state. Further investigation revealed that in these runs, the distribution of objects in the initial layouts did not allow them to freely move in the direction of their resultant force. Interestingly, it was observed that all the remaining 851 runs resulted in exactly nine (9) layouts. Fig. 9 shows these nine layouts in increasing order of the objective function (i.e. decreasing fitness).

L1 (top-left) is the layout with the lowest objective function (40,454) and represents the optimum layout (Fig. 9). Fig. 10 shows the changes in the objective function for one of the 1000 runs that resulted in L1 layout. It took the model 32 ms to reach the final layout for this specific run. As it can be seen from Fig. 10, no change is observed in the objective function after 32 ms. A stable value for the objective function means that the forces (closeness weights) acting on objects are balanced, and as a result, objects stop moving. At this point the minimum objective function, and accordingly the optimum layout, has been reached.

It is worth noting that in the optimum layout presented in Fig. 11, the security office (CO6) appears to overlap with the rebar workshop and the batch plant (Objects CO1 and CO3). However, this is not an actual space conflict since the security office does not exist on the site at the same time as the rebar workshop and the batch plant (see Table 1). In fact, the security office which exists on the site during months 8 to 10, reuses the space that was used by the rebar workshop and the batch plant during months 1 through 7. The other interesting point in this layout is that although the rebar workshop (CO1) and the

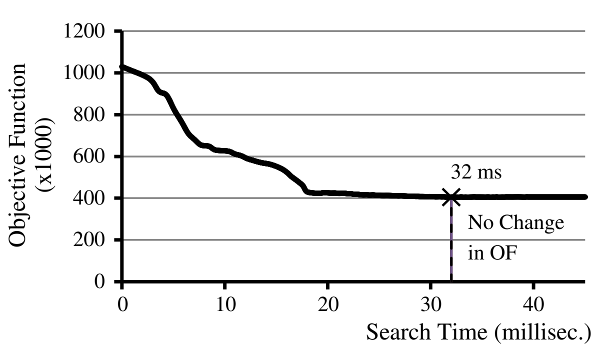

Fig. 10. Change in the objective function during search for equilibrium state.

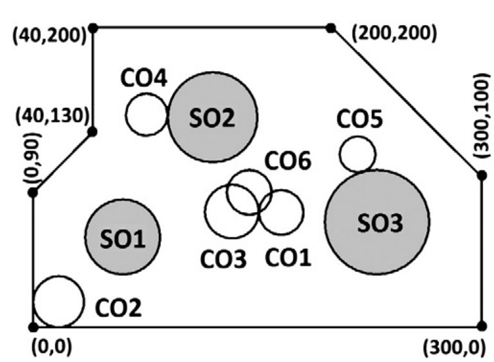

Fig. 11. The optimum layout for the case example.

batch plant (CO3) do not have any closeness weight with each other, they end up being adjacent in the final layout. This means that these two objects were competing over the same space based on their closeness weights with other objects. This situation typically results in two objects pushing each other to occupy the desired space until the object with larger closeness weights pushes the other one and both objects reach a balanced state.

Fig. 12 shows the value of the objective function for these nine layouts along with their frequency of occurrence in the 1000 runs. While it is sufficient to reach the global optimum layout only once during all the runs to ensure it is identified, this layout has been reached in 260 of the 1000 runs in this example.

9.1. Discussion

Due to the random generation of the initial layout, the search process is repeated several times to ensure it does not get trapped in the local optimum. It is important to estimate how many runs are needed to ensure that the global optimum is reached. In order to study how many initial random layouts are required to ensure that the global optimum layout is reached at least once, 100 sets of runs were conducted for the aforementioned numerical example. In each one of the 100 sets, the model was run several times to generate final layouts from random initial layouts until the known optimum layout L1 (Fig. 11) was achieved. Fig. 13 shows the total number of runs conducted in each set to reach the global optimum layout. It was observed that on average, the global optimum layout was found after only 3.2 runs. Since the search process has a random basis, a probability analysis can determine the confidence level of finding the global optimum layout. The probability of reaching the global optimum at least once after 'n' trials can be calculated with the following probability function [35]:

$$\text{Probability Function} = 1-(1-p)^n \tag{4}$$

where p is the probability of reaching the global optimum in one trial, and n is the total number of trials. Since the mean value for this example was 3.2 runs, it can be said that the probability of reaching the global optimum in 3.2 runs is 50%. The probability of finding the global optimum in one trial (p in Eq. (4)) can therefore be calculated as:

$$1-(1-p)^{3.2} = 0.5$$
$$p = 0.195.$$

Accordingly, the required number of runs in order to reach the global optimum layout with 99.9% confidence can be determined as:

$$1-(1-0.195)^n = 0.999$$
$$n = 32 \text{ runs}.$$

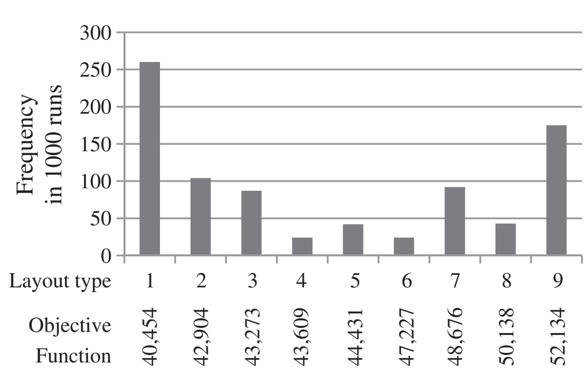

Fig. 12. Frequency and objective function for the 851 generated final layouts.

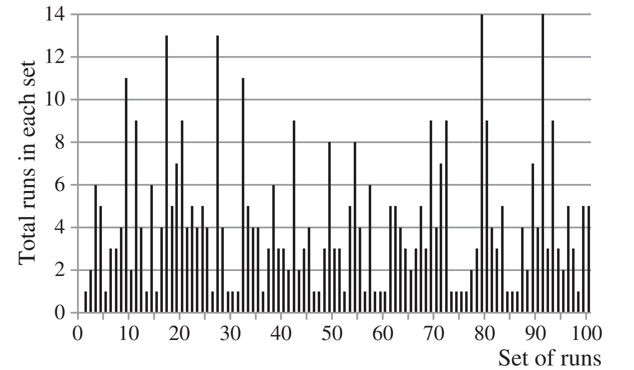

Fig. 13. Number of runs conducted in each set of 100 tests to reach the optimum layout.

Similarly, for 99% confidence, 22 runs will be required. The above calculations mean that if 32 random initial layouts are generated for the presented case example, with 99.9% confidence, it can be assumed that at least one of them will result in the global optimum layout shown in Fig. 9. Although this number can change for different scenarios, this example demonstrates that the model is able to determine the global optimum layout in relatively small number of runs. Since the developed model can converge layouts quickly (31 s for 1000 runs in the example), choosing a large number of runs can ensure that the global optimum layout is reached. Further investigations will be needed to study how variables, such as the number of objects and the size of site, can impact the time and the possibility of reaching the global optimum layout.

10. Summary and concluding remarks

The objective of this study was to provide a methodology for developing dynamic construction site layouts that are optimized over the duration of the project, while reflecting the actual changes on the site, in terms of object requirements and relationships between objects. As such, dynamic site layout can be conceptually viewed as a problem in which a multitude of objects, with different temporal and spatial dimensions, and different proximity relationships, compete over best locations in a given space. The temporal aspects of dynamic site layout have made dynamic site layout a challenging problem. As a result, site layout is often simplified into a static or phased rendition. Due to its similarity in concepts and interactions between its defining elements, this research explored the possibility of using a well known concept from physics, Minimum Total Potential Energy, to model dynamic site layout planning. Parallels were drawn between objects in a construction site that have different closeness relationships between them and particles in a physical system that move under the influence of their internal forces. A dynamic site layout model was developed based on the proposed methodology and it was demonstrated that use of the MPTE principle is an efficient method for generating dynamic site layouts that are optimum over the duration of the construction project.

A key feature of the model is that it considers the *actual* duration for which objects are required on the site in the process of optimization (unlike static and phased models). This feature enables the reuse of the same space by different objects over the course of time. Another important aspect of the model is that it allows for a simultaneous search for the optimum location of *all* the objects that are required in different periods of the project. In other words, it allows all objects, regardless of the time and order in which they arrive on the site, to have an equal chance to compete over optimum locations for the specific time that they are required on the site. This feature is enabled by the MPTE principle and is quintessential to the development of the dynamic site layout model. The model presented in this paper is the first dynamic layout planning model to generate site layouts that are optimized over the duration of the construction project while considering the actual duration of objects on the site.

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