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The time dimension in site layout planning

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ABSTRACT

With regard to incorporation of the time factor, site layout models are traditionally grouped into two categories of *static* models (with no considerations of the changes over time), and *dynamic* models (reflecting the changes on the construction sites). This paper demonstrates that there are in fact fundamental differences in the assumptions and the final outcome of models that are currently all categorized under dynamic site layout planning models, and proposes that these should in fact be divided into two groups of *phased* and *dynamic* models. The paper provides a comparative analysis of the three approaches of *static*, *phased* and *dynamic* site layout planning. The strengths, limitations, and differences in the final results of the three approaches are demonstrated through numerical examples. Finally, existing methods for the 2D representation of dynamic site layouts are compared, and an improved algorithm is provided to represent dynamic site layouts in minimum number of overlap-free drawings.

1. Introduction

Different objects such as tower cranes, batch plants, management offices, material storage areas, and workshops are required on the site to support construction activities. These objects are often allocated space on a first-come first served basis — e.g., the objects take the best available location at the time of their arrival on the site. In the long run, this may decrease the efficiency of site operations. Studies have shown that front-end planning of the layout of the construction site can contribute to a decrease in the cost of material handling and workflows between objects, and to an increase in the safety and productivity of projects [1,2]. Determining the optimum location of objects on the construction site is referred to as site layout planning [1,3]. Site layout planning has attracted the attention of researchers in the past three decades, and several models have been developed for the optimization of construction site layouts. The common objective of these models is to determine the optimum location of objects in the available space on the site, while considering the workflows between objects. Although all models share this general objective, they have adopted different approaches in the way they define and address the problem. Due to the complex nature of construction sites, a large number of parameters are involved in modeling site layout planning. This paper focuses solely on one of the main parameters, namely the "time factor".

The "time factor" determines how changes that occur on the site during the course of project are reflected in the site layout model. As the project progresses, the construction activities change, and accordingly the supporting objects associated with these activities are subject to change as well. This dynamic nature of construction sites defines one of the main challenges in site layout planning, namely the incorporation of the time factor in the optimization of layouts. The incorporation of time factor changes the construction site layout problem from a 2D or 3D optimization problem – i.e. one that only includes physical dimensions – into a 4D optimization problem, by adding the time dimension to the physical dimensions. In other words, unlike floor planning, construction site layout planning is not simply a space optimization problem, rather an optimization of space over time.

In the past few decades, different approaches have been used for representing the time factor in site layout planning, and the research has evolved over time. Inspired by plant layout planning (e.g.[4]), the first generation of site layout models ignored the changes that occur on construction sites, and generated a single layout for the entire duration of the project. These models are referred to as *static* models. In later studies, the importance of incorporating the time factor in site layout models and reflecting the changes on the construction site was recognized. The next generation of site layout models considered the time factor and incorporated the changes that occur on the site over the course of time in the optimization of layouts. In existing literature, any consideration of time factor in site layout models has been referred to as "dynamic" layout planning. However, as this paper will demonstrate, there are major differences between these models, and grouping them collectively under the same term is inaccurate and ignores the differences between them.

In this paper, a distinction is made between two approaches that consider the time factor in the optimization process. These two approaches differ significantly from each other, and can consequently lead to very different solutions. The paper first provides a comparative

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analysis of the different approaches for modeling the time factor in site layout models. The impact of the time factor on the generated layout is then demonstrated through numerical examples. In the final section, the paper focuses on visual representation of a dynamic site layout in 2D space of paper documents. Two existing representation methods from literature are compared, and an improved method is proposed for representing a dynamic site layout in a way that facilitates the on-site communication of information related to site layout planning.

2. Approaches to representing the time dimension in site layout planning

The role of construction objects such as equipment, material, workspaces and temporary facilities is to support construction activities. The time and duration for which the objects stay on the site depend on the activities that they are associated with [5]. As the project progresses and construction activities change, the required objects, and accordingly, the space required on the site to accommodate them, are subject to change. Different approaches have been used in literature to represent these changes in site layout planning. As mentioned above, these approaches were generally identified either as static, when they don't reflect changes, or as dynamic, when they reflect changes over time. However, close examination of models previously identified as dynamic reveals that they can in fact be grouped under two separate approaches: one of which is *phased*, while the other is actually *dynamic*. This section provides a comparative analysis of the main underlying assumptions that differentiate between *static*, *phased*, and *dynamic* approaches for representing the time factor in site layout planning through an illustrative case.

2.1. Static approach

In the static approach, it is assumed that all objects are required for the entire duration of the project, and hence, do not allow two objects to use the same space on the site [1–3,6–30]. In this approach, the optimum location for each object is searched regardless of its duration of existence on the site. The advantage of this assumption is that it simplifies the search process. The static approach can be considered suitable and sufficient for short-term projects with a large available site space, where there are few changes that occur on the site and the available space is abundant. However, for more complex projects with longer durations, where numerous objects arrive and leave the site over the course of construction, the *static* approach will be limiting. Since the changes in site space requirements are not reflected in the *static* approach, the reuse of the space that was previously occupied by other objects is not considered [31,32]. As a result, the *static* approach does not provide a realistic representation of space requirements, and consequently, does not lead to an efficient use of space.

2.1.1. Case example

To illustrate the importance of incorporating changes in the space requirements over the duration of a project, consider the following example. Assume a construction project with 800 m^2 of available site space and nine (9) objects. The objects have different sizes and are required on site for different periods of the construction project, as shown in Fig. 1. In the reality of construction sites, objects can be assigned to any available space when they arrive to the site. For instance, the Batch Plant (object C) in this example requires 120 m^2 on the site between months 5 and 12. This object can be assigned to any available space at month 5 including the space that was occupied by the Geotechnical Lab (object A) during months 1 through 4. Similarly, the space occupied by the Batch Plant (C) can be reused for objects that enter the site after month 12 (i.e. Carpentry Shop (E) and Landscape Shop (I)). However, since the changes in space requirements are ignored in the *static* approach, in fact it does not allow the reuse of site space. The Geotechnical Lab (object A) and the Batch Plant (object C) in this example would not be allowed to use the same space in the *static* approach, even though in reality they do not exist on the site at the same time.

The space requirements for accommodating the objects on the site over the course of a project can be presented using a space histogram [33] (Fig. 2). The area under the histogram curve reflects the time–space requirement for the project; i.e. the total amount of space required to accommodate all the objects over the course of project. The time–space requirement of a project can be determined as follows:

$$\text{Time–Space Requirement} = \sum A_i \times T_i \quad (1)$$

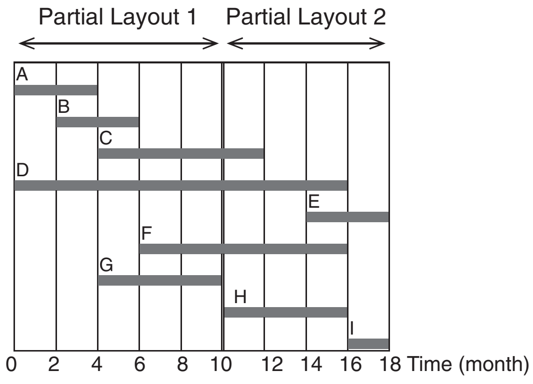
where A_i is the footprint area for object i, and T_i is the duration that object i exists on the site. Since changes are not considered in the *static* approach, it is as if it is assumed all objects that exist on the site for the entire duration of the project. This assumption means that in the static approach, the space required to accommodate objects at any given time is equal to the sum of the footprints of all the objects (900 m^2 in this example). Accordingly, the time–space histogram will be a straight line, indicating that space requirements do not change over time in the static approach (see Fig. 2). The total required time–space (i.e. space required over the duration of the project) for the example illustrated in Fig. 1 in the *static* scenario can be calculated using Eq. (1):

$$\begin{aligned}\text{Time–Space Requirement}_{\text{static}} &= (100+90+120+110+80+70+130+120+80)\times 18 \\ &= (900)\times 18 = 16{,}200 \quad \text{month-m}^2.\end{aligned}$$

The unit month-m^2 is used to refer to the space needed over a specific period of time (m^2 over time) to distinguish it from the footprint of objects (m^2). The total time–space available for this

ID	Name	Size (m^2)	Duration (month)	Time-Space month-m^2
A	Geotechnical Lab	100	4	400
B	Rebar Shop	90	4	360
C	Batch Plant	120	8	960
D	Offices	110	16	1760
E	Carpentry Shop	80	4	320
F	Storage	70	10	700
G	Gravel Depot	130	6	780
H	Brick Depot	120	6	720
I	Landscape Shop	80	2	160

(a)



(b)

Fig. 1. Case example; a. Construction objects properties, b. Construction objects schedule.

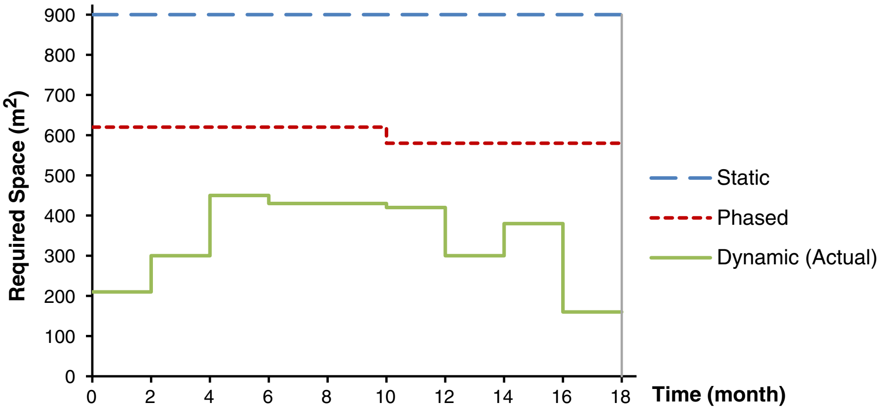


Fig. 2. Comparing space histogram for the three approaches: static, phased, and dynamic.

project can be calculated as a function of site area and project duration:

$$\text{Total Available Time–Space} = 800 \times 18 = 14,400 \quad \text{month-m}^2.$$

The above two values imply that it is impossible to locate all nine (9) objects on the site, since the total available time–space (14,400 month-m^2) would be less than the required time–space (16,200 month-m^2) in the *static* approach. In other words, planning the layout using the *static* approach for this example will indicate a shortage of site space, while in reality – as will be shown in the following sections – this is not the case.

2.2. Phased approach

To overcome the limitations of the static approach and reflect the changes over time, some studies proposed dividing the project duration into several time intervals and generating a partial layout for each phase [5,31,33–37]. The duration of each phase (time interval) is decided by the planner based on experience [5]. In each partial layout, the locations of objects that exist in that time interval are optimized. Objects that remain on the site from one time interval to the next are considered fixed in the location they have been allocated in the previous layout, while the rest of the objects that are required in that time interval are optimized in the remaining space. As a result, the *phased* approach allows the reuse of space from one phase to another. In other words, in each phase the space that was occupied by objects from the previous phase, which are no longer on the site in the new phase, can be reused to accommodate new objects.

Case example: Using the example in Fig. 1, it is assumed that the duration of the project is divided into two time intervals: the first one from months 1 to 10, and the second from months 11 to 18 (see Fig. 1). Objects that enter the site in the second time interval (i.e. Carpentry Shop (E), Brick Depot (H), and Landscape Shop (I)) are allowed to use the space of objects from the first time interval that are no longer required (i.e. Geotechnical Lab. (Object A), Rebar Shop (Object B), and Gravel Depot (Object G)). Compared with the *static* scenario, the *phased* approach enables a more efficient use of the site space, and hence can lead to more efficient layouts. For instance, in the above example, only six (6) objects compete over the prime locations during each time interval when the phased approach is used, while in the *static* approach nine (9) objects are competing over the same space. Locating fewer objects (6 compared to 9) in the same space decreases the competition over the same space and increases the possibility of objects to be assigned to better locations, which in turn will result in improved layouts.

Despite their advantage over *static* models, *phased* models are challenged by disadvantages of their own. Although space can be reused from one partial layout to another in phased models, within each partial layout space reuse is not allowed [38]. For example, when the Gravel Depot (Object G) in Fig. 1 enters the site, it cannot take the space of the Geotechnical lab (Object A), even though the latter object is not on the site anymore. As a result, in the *phased* approach, the required space can change from one time interval to another, but remains constant for the duration of each time interval. In the above example, the time–space required in partial layout 1 is 620 m^2, and 580 m^2 in the second time interval (see Fig. 2).

In addition, in phased models each partial layout is often optimized separately in a chronological order [34,35]. This means that the locations of objects in later time intervals (i.e. Carpentry Shop (E), Brick Depot (H), and Landscape Shop (I)) are highly influenced by the location of objects in the earlier time intervals (Batch Plant (C), Offices (D), and Storage (F)). This approach will not be efficient for cases where more important objects arrive on the site during later phases of the project. In addition, and more importantly, combining separately optimized layouts does not necessarily lead to a layout that is optimum over the entire duration of the project [31,38]. This will be demonstrated in Section 3.2 through an example.

2.3. Dynamic approach

In the *dynamic* approach, the "actual" duration that objects occupy space on the site is considered for the optimization [32,39]. Accordingly, objects that belong to different periods of time are allowed to occupy the same space on the site. For instance, the Landscape Shop (object I) in the previous example only competes with the Carpentry Shop (object E) to find its optimum location and would have plenty of space available on the site. In reality, objects enter and leave the construction site at different points of time in the project, and assigning space to them for longer durations than they are on the site will reduce the efficiency of the final layout.

Case example: To demonstrate this through a numerical example, using Eq. (1) and the *actual* durations of the objects on the site, the *actual* time–space required for the project in the aforementioned example can be calculated as:

$$\begin{aligned}\text{Time–Space Requirement}_{actual} &= 100 \times 4 + 90 \times 4 + 120 \times 8 + 110 \times 16 + 80 \times 4 + 70 \times 10 + \\ &\quad 130 \times 6 + 120 \times 6 + 80 \times 2 \\ &= 6160 \quad \text{month-m}^2\end{aligned}$$

while the overall time–space required to for accommodating all objects in a *phased* approach will be:

$$\begin{aligned}\text{Time–Space Requirement}_{(\text{phase 1})} &= (100+90+120+110+70+130)\times 10\\ &= 6200 \quad \text{month-m}^2.\end{aligned}$$

$$\begin{aligned}\text{Time–Space Requirement}_{(\text{phase 2})} &= (120+110+80+70+120+80)\times 8\\ &= 4640 \quad \text{month-m}^2\end{aligned}$$

$$\text{Time–Space Requirement}_{phased} = 6200+4640 = 10,840 \quad \text{month-m}^2.$$

As can be seen, the estimated time–space required to accommodate all nine (9) objects using the *phased* approach is 75% more than the *actual* required time–space. Using the *phased* approach can lead to an over-allocation of site space, and may accordingly reduce the efficiency of the generated layout. The difference in the overall time–space requirements in the *phased* approach and *dynamic* approach (in which the actual duration of objects is reflected) can also be compared in the time–space histogram in Fig. 2. To generate the histogram for the dynamic approach, the spaces required for objects at any point in time are added together. For instance for the first month (0 to 1) only two objects exist on the site (A and D), and accordingly, the summation of their sizes (100 + 110) would show the value of the histogram (210) for this time period. As can be inferred from Fig. 2, the histogram for the *phased* approach indicates a higher level of space requirement for the first time interval (620 m^2 per month), suggesting that the site will be highly crowded during the first 10 months. However, the time–space histogram for the *dynamic* approach shows that the highest level of space requirements occurs only between month four (4) to month six (6) and with a more modest space requirement (450 m^2 per month). This is due to the fact that in the *phased* approach, objects are assumed to be present on the site for the entire duration of the *time intervals* they belong to. The simplification assumption leads to an over-estimation of time–space requirement in the phased approach, which decreases objects' chances to be assigned to better locations on the site. In other words, in reality, no more than four (4) objects are required on the site at any given time in this example, while in a *phased* approach six (6) objects will be competing over optimum positions in each partial layout.

The *dynamic* approach provides the opportunity to make the most efficient use of space and generate layouts that are optimized over the duration of the project. This is especially critical for projects with a small construction site space and many objects, such as projects in dense urban areas. In such projects, dynamic layout planning can assist in making an efficient use of space as a scarce resource.

3. The impact of time modeling approach on the resulting site layouts

As demonstrated in the previous section, the use of different time modeling approaches can impact the assumption for the overall site space required to accommodate construction objects. However, the choice of approach may also affect the locations of objects, and hence the optimality of the resulting layout in terms of the defined objective. Even the *phased* and *dynamic* approaches – which in previous research were not distinguished from each other – can result in very different outcomes. This section compares the impact of each one of the three approaches on the generated site layout through a numerical example.

In order to compare the impact of the approach used in modeling the time factor, a site layout example is optimized using the *static*, *phased*, and *dynamic* approaches. Consider a construction project with two (2) buildings under construction with known locations, and five (5) supporting objects that need to be located on the site. The site premises and dimensions, along with the location of the two buildings are shown in Fig. 3. For simplicity, objects are represented by a bounding circle and distances between objects are measured from the centers of the bounding circles. The sizes of the objects and the duration of their presence on the site are listed in Table 1. For the sake of discussion, we consider for this example the simple objective of minimizing the total weighted distance between objects that have workflows between them. Needless to mention, it is possible to define more sophisticated objectives for a site layout problem. The minimization of the total weighted distance is selected here as it is a commonly objective used in literature [11,14,16,28] and since it is sufficient for the purpose of the discussion intended in this paper. The following objective function (OF) is used for the optimization:

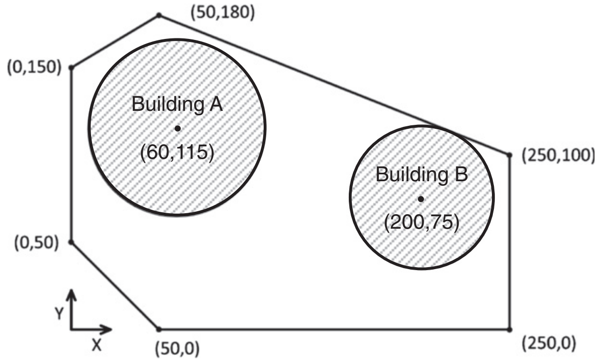


Fig. 3. Site premises and the location of buildings under construction.

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

where W_{ij} is the closeness weight between objects i and j, and d_{ij} is the distance between them. The closeness weights can be assigned by a site planner, and represent the cost of workflows and material handling between each pair of objects. Although the actual costs can also be used to determine the weights, relative values are often used to indicate how close to each other two objects are desired to be located [10,17,24]. The closeness weights assumed for the objects in this example are presented in Table 1. The optimum site layout is achieved by finding the location for objects such that the objective function presented in Eq. (2) is minimized.

The example is solved using a dynamic site layout planning model previously developed by the authors (MPTE model) [39]. This model was used due to its availability to authors and its capability to generate optimum site layout plans in all three time modeling approaches of *static*, *phased*, and *dynamic*. In addition, the model's ability to generate optimum layouts has been validated. The model uses Minimum Total Potential Energy (MPTE) principle from physics to optimize the layout of site objects based on the importance of closeness between every pair of objects. In the MPTE model, objects are represented as *particles* in a *physical system* and the closeness weights between objects are represented as *internal forces* between the particles. Site layout objects are initiated at a random location on the site. Just as particles in a physical system, site layout objects, move around the site space under the influence of their internal forces (closeness weights) until they reach the *equilibrium state*. Based on the MPTE principle, particles in a physical system have the lowest possible potential energy at the equilibrium state. Accordingly, at the equilibrium state the objective function of the layout will also be at its minimum value and the arrangement of objects on the site at that point represents the optimum layout — with minimum total weighted distance. For more details on the functionality of the model readers are referred to [39]. It should be emphasized that the choice of the model or the optimization technique used to solve

Table 1
Object properties and their closeness weights with Buildings A and B.

Object	Size	Closeness weight		Duration (months)											
	(Radius)(m)	bldg A	bldg B	1	2	3	4	5	6	7	8	9	10	11	12
Building A	50	–	–	A ■	■	■	■	■	■	■	■	■	■	■	■
Building B	40	–	–	B ■	■	■	■	■	■	■	■	■	■	■	■
C	12	45	30	C ■	■	■									
D	15	50	40				D ■	■	■						
E	35	60	60	E ■	■	■	■	■	■	■	■	■			
F	22	55	40							F ■	■	■	■	■	■
G	15	95	85										G ■	■	■

the example would neither change the resulting layout, nor does it affect the discussion intended in this paper and the consequent conclusion. The resulting layouts for each of the three approaches are shown in Fig. 4. Table 2 summarizes the location of objects, the value for the object function (OF) and the time–space requirement for each one of the respective layouts.

In line with the results from the example in the previous section, the total time–space requirements decrease when a phased approach is used to generate an optimum layout, and even more so when a dynamic approach is used (Fig. 5). However, the objective function measured for the optimum layouts generated with each one of the approaches is an even more informative indicator of their efficiency, and as will be explained below, it leads to some counterintuitive findings.

3.1. Discussion on the static layout

Static approach does not allow the same space to be used for several objects (Fig. 4a) even though they do not exist on the site at the same time. For instance, objects C and D both have the same desired location (this can be clearly inferred from their location in the *dynamic* layout — Fig. 4c). However, they cannot use the same space in the *static* approach, even though they will be on the site at different times. Instead, in the static layout these two objects will be located adjacent to each other, and close to their desired location. Based on Eq. (2) and using the location of objects in the final layout (Table 2) and the closeness weights from Table 1, the value of the objective function for the static layout is 44,018.

3.2. Discussion on the phased layout

In the *phased* layout (Fig. 4b) the project duration is divided into two time intervals – from the 1st to the 6th month (phase 1) and from the 7th to the 12th month (phase 2) – and an optimum partial layout is generated for each time interval in chronological order. This means that objects C, D, and E (from phase 1) will be located before objects F and G (from phase 2). Object E belongs to both time intervals but it is located in the first partial layout and remains fixed on its previous location in the second phase (see Fig. 4b). Therefore, in the second time interval, objects F and G will have less of an opportunity to obtain their desired locations, compared with object E. As a result, the *phased* approach in this example results in even a less optimum layout than the one generated using the *static* approach ($\text{OF}_{\text{phased}} = 44{,}310$ compare to $\text{OF}_{\text{Static}} = 44{,}018$). This can be attributed to the fact that objects F and G, which have higher closeness weights (see Table 1), are given the last priority in the location optimization. This simple example shows that although *phased* approach allows limited reuse of space from one partial layout to another, it does not necessarily result in better layouts than the *static* approach.

Another shortcoming of the use of *phased* layouts is the impact of the order in which partial layouts are optimized. To demonstrate this impact, the above example is solved in reverse order of partial layouts; first the partial layout for the phase 2 is generated, and then partial layout for phase 1. The results are shown in Fig. 6 and Table 3. The objective function in this case (43,077) is better than when the partial layouts were generated in chronological order. In fact, this improvement in the objective function could be predicted. A look at the closeness weight table indicates that objects E and G had higher closeness weights, and as a result carry a higher importance in the score of the final layout. Optimizing the phased layouts in reverse order helps the more important objects of E and G to get to their desired locations before C and D are allocated space, resulting in better overall OF. This simple example shows another drawback of phased layout approach — namely, that the order in which partial layouts are optimized can have an impact on the quality of the final layout.

To add to the previous point, it is not only the *order* of the partial layouts, but also the *durations* selected for them that can impact the resultant layout in the phased approach. For example, if in the above example, the two phases are defined at the end of the 3rd month (resulting in two time intervals of months 1 through 3 (phase 1) and 3 through 12 (phase 2)), or if it is instead defined at the end of 9th month (resulting in two time intervals of months 1 through 9 (phase 1) and 9 through 12 (phase 2)), the final layout and the objective function will change again as shown in Fig. 7 and summarized in Table 3.

The importance of the above variations can become more evident when it is kept in mind that time intervals in the *phased* approach are manually selected by the user, and no methodology currently exists for the definition of the optimum number of time intervals, their optimum order, or their optimum durations, in order to achieve the best result and the minimum objective function. Although the *phased* approach reduces the overall site space required for the construction objects, as compared to the static approach, it does not necessarily generate a better layout with regard to the defined objective function. The results of this comparison also show that the order in which construction objects are allocated site space can have a major impact when using the *phased* approach. This indicates that the sum of a series of optimized partial layouts does not necessarily result in a layout that is optimized over the entire duration of the project.

3.3. Discussion on the dynamic layout

Fig. 4c shows the layout generated using the *dynamic* approach. This approach uses the actual durations of objects and yields the best objective function compared to the previous two approaches ($\text{OF} = 41{,}968$). This improvement is due to the advantages of the dynamic approach over the other two approaches; unlike the *static* approach, space is not over-allocated in the dynamic approach, since every object is assigned a space only for its actual duration on site. In addition, in the dynamic approach, time is considered a continuous dimension in the optimization, and therefore unlike the *phased* approach, there are no discrete time intervals (or phases) whose order can affect the final result.

It should be noted that although objects C, D, and F on the one hand, and G and E on the other hand, may appear to have space conflict in this layout, this is only an illusory overlap. Since these objects are not on site at the same time, there is no space conflict between them in reality, and they can occupy the same space on the site. The illusory overlap is due to the fact that the dynamic layout is represented in 2D space (e.g. paper). The illusory overlaps in *dynamic* layouts lead to interesting issues regarding the communication of site layout information that will be discussed in the next section.

To conclude, this simple example shows that the use of a *dynamic* approach to reflect the time factor leads to a better layout, with a lower objective function, compared with the *static* and *phased* approaches. The example also specifically highlights the clear difference between the *phased* and *dynamic* approaches, which have been previously overlooked in literature. Therefore, unlike what is generally assumed, not *every* consideration of time in the generation of layouts should be classified as *dynamic* layout planning.

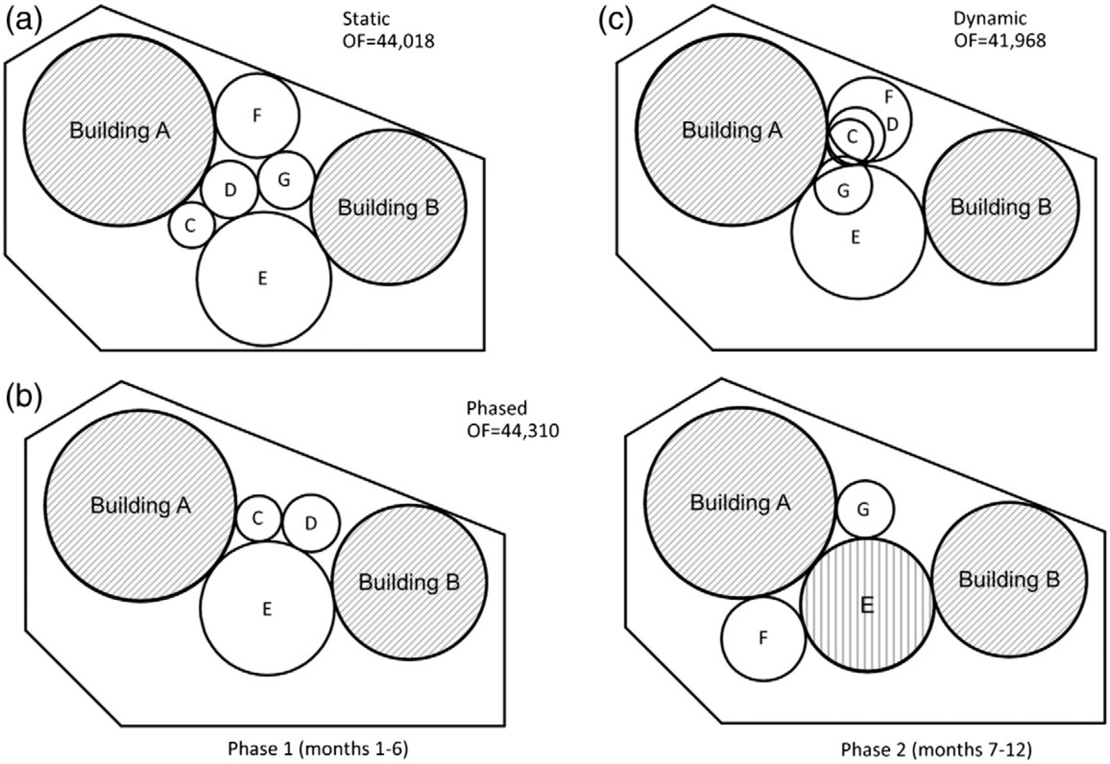


Fig. 4. Optimum layouts generated using the three approaches of time modeling: a. Static, b. Phased, and c. Dynamic.

4. Presenting dynamic site layouts in construction documents

Site layouts are used by site personnel as a guideline for the location of objects as they arrive on the site. 2D blueprints are still the most common form of representation of site layouts. In a layout generated with the *dynamic* approach, multiple objects may use the same space on the site at different points of time. Accordingly, if all the objects are presented in a single 2D document, they could appear to have space overlaps (see Fig. 4c) — which can be confusing for the day-to-day operations of the site. The reason behind this illusory overlap is, obviously, that the 4D space of site layout (2D or 3D physical dimensions + time) is represented in a 2D space of a plane. To avoid such confusions and make the reading of dynamic site layouts more clear, an algorithm is proposed for representing 4D *dynamic* layouts in a minimum number of overlap-free 2D drawings. This section first explains the reason behind this confusion from geometric perspective, then explains the proposed algorithm, and demonstrates its advantage over the previous approaches through a numerical example.

4.1. Geometric perspective

The illusory overlap of objects in dynamic site layout can be viewed as being similar to that of two skew lines when presented in a 2D planar space. Although two skew lines do not intersect in the 3D space, they could appear to be intersecting when represented on a 2D plane. In general, when objects are represented in a geometric space that has fewer dimensions than the collection of objects themselves, they may appear to have intersections that do not exist in reality. This illusory intersection occurs when the dimension that differentiates the locus of the objects is lost in a representation space with fewer dimensions.

Table 2
Location of objects, objective function (OF) and time–space requirements for the three optimum layouts.

Object	Static		Phased		Dynamic	
	X	Y	X	Y	X	Y
C	79.50	65.626	121.65	108.46	121.65	108.46
D	117.19	84.103	148.57	106.39	124.91	111.66
E	135.09	37.420	126.19	61.68	126.19	61.77
F	131.59	122.668	72.00	44.01	131.79	120.47
G	146.79	88.937	124.91	111.66	118.20	86.06
Objective function	44,018		44,310		41,968	
Time–space (month–m2)	241,265		220,955		203,820	

In *dynamic* site layout planning, objects with illusory overlaps may in fact be occupying the same space, but only at different times. To visualize the time–space occupied by objects, assume a coordinate system where the z axis represents the time dimension. To represent the time–space that objects occupy, the footprint of objects in the XY plane (i.e. the site) is extruded for the duration they exist on the site.

As an example, Fig. 8a presents the schedule for three objects and Fig. 8b shows the 2D presentation of their location on the site. The 3D extruded view of objects A, B, and C, where each exists on the site for a different period of time, is presented in Fig. 8c. Representing all three objects in a single 2D plane (Fig. 8b) is similar to view the 3D space from the top and along the Z axis. Since the z dimension (time) is not represented in the 2D "top view" (i.e. plan view), the objects *appear* to have space overlaps.

4.2. Presenting 4D site layouts in 2D space

On construction sites, blueprints and paper documents are still the most practical methods for sharing information with project team members. Showing a dynamic layout in a single drawing that contains illusory overlaps, such as the one shown in Fig. 4c, can be confusing for the day to day operations of the site. To avoid the confusion caused by illusory overlaps in 2D views, it is suggested to present the dynamic layout in a series of consecutive 2D drawings, each representing different time intervals in the construction project [40,41]. Each drawing shows the location of objects for a specific duration of the construction project, and together, they represent the entire duration of the project. It should be noted that these consecutive drawings should not be confused with the *partial layouts* used in the phased approach. Here, the series of

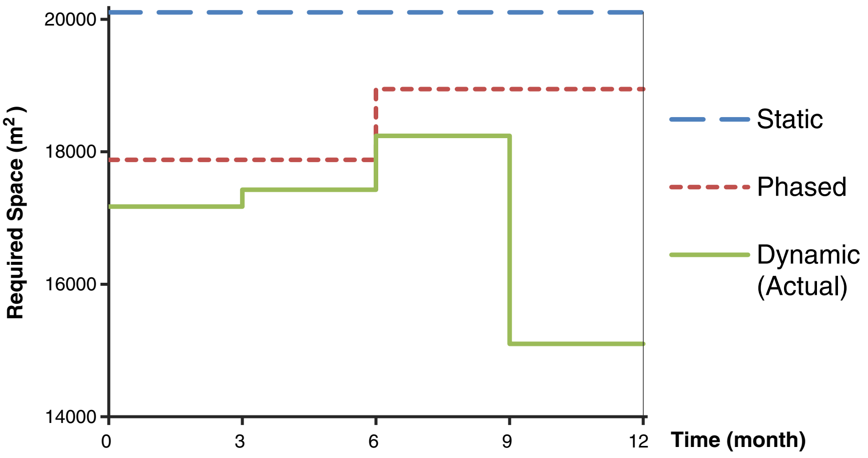


Fig. 5. Space histogram for static, phased, and dynamic approaches.

drawings are used for representation purposes only, *after* the optimum locations of objects have been identified, whereas in the phased approach the partial layouts are generated as *part of* the optimization process. In other words, these consecutive drawings can be looked at as an "exploded view" of the dynamic layout over the time axis.

The main question in presenting 4D site layouts in a series of 2D documents for effective and clear communication is how the time intervals for these drawings are selected to ensure that they are free of illusory overlaps, and that at the same time the minimum number of drawings are used [42]. One of the earliest studies on construction site layouts suggested using fixed time intervals (e.g. every 3 months) for generating the series of site layout drawings [40]. Although this method is easy to implement, it does not guarantee that the documents are free of illusory overlaps as it will be shown in an example in Section 4.3. To avoid such overlaps, Zouein [41] suggested generating a new partial layout every time a new object(s) enters the site. For instance, for the example presented in Fig. 1, seven (7) partial layouts will be generated for a project with nine (9) objects. This approach will certainly eliminate the possibility of including any illusory overlap in the documents. However, it brings the number of layout drawings almost equal to the number of objects involved in the project. The reason for this excessive number of documents is that this approach does not consider the possibility of merging consecutive layout drawings when they do not include an illusory overlap. This might cause a logistic burden; the less the information is spread between documents, the easier and more effective to manage them.

A new algorithm is proposed here for generating a representation of a dynamic site layout for the entire duration of the project, using a minimum number of partial layouts that do not include any illusory overlaps. The essence of this approach is that the arrival of new objects on site is not a *sufficient* condition for generating a new layout drawing. Instead, in the proposed approach, a new layout drawing is generated only and only when a new object entering the site has an illusory overlap with one of the objects in the current layout drawing. The algorithm contains the following steps:

Step 1. Initiation An empty layout (L) is generated for the beginning of the project (T = 0).
Step 2. Adding objects to layout drawings The objects are added to the current layout drawing (L) one at a time, and in chronological order (i.e. the order they enter the site) on the location assigned to them in the optimization. When two or more objects enter the site at the same time, they are all added to the layout drawing at the same time. This step is continued until an illusory overlap occurs.
Step 3. Creating a new layout drawing When an illusory overlap occurs, the object that caused the overlap is removed from the layout; the current layout (L) is closed; and a new layout drawing is generated (L = L + 1).
In this new layout, objects from the previous layout that continue to exist on the site are first plotted in their known locations. Then the object that caused the illusory overlap in the previous layout drawing is added to the new drawing. The addition of objects is continued as described in step 2.
Step 4. Termination Steps 2 and 3 are continued until all objects are assigned to layout drawings.

Fig. 9 presents the flowchart for the proposed algorithm.

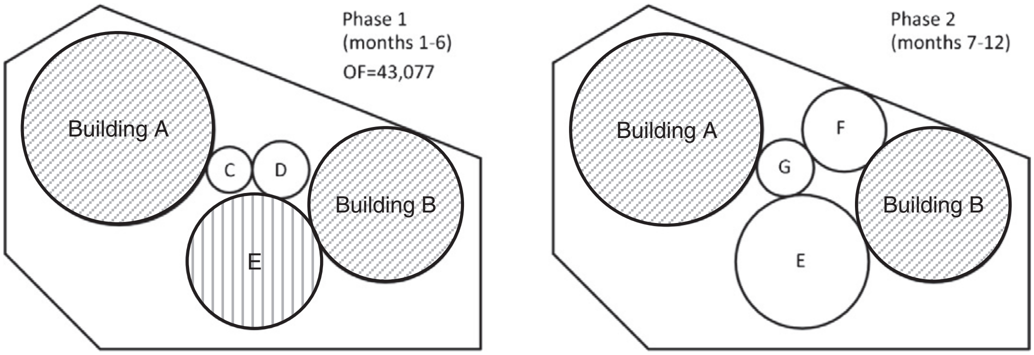


Fig. 6. Resulting layout for phased approach when the phase 2 is optimized first.

Table 3
Comparing the results of different alternatives for the phased approach.

Object	Time intervals (in months)							
	@month 3		@month 6		@month 6 — reverse		@month 9	
	(1–3) & (4–12)		(1–6) & (7–12)		(7–12) & (1–6)		(1–9) & (10–12)	
	X	Y	X	Y	X	Y	X	Y
C	121.65	108.46	121.65	108.46	118.48	94.41	117.81	92.55
D	124.99	114.18	148.57	106.39	145.47	93.61	147.14	90.20
E	126.19	61.68	126.19	61.68	130.93	45.77	123.82	45.97
F	72.00	44.01	72.00	44.01	152.79	115.19	131.47	123.72
G	153.14	103.79	124.91	111.66	121.83	94.93	119.45	88.72
Obj. function	44,396		44,310		43,077		43,017	
Time–space (month-m^2)	228,397		220,956		220,956		219,891	

4.3. Case example

The example introduced in Fig. 1 is used here to demonstrate the efficiency of the proposed method for representing a dynamic layout using a minimum number of drawings without illusory overlaps. The schedule and size of the objects involved in the project can be found in Fig. 1. The shape and dimensions of the site and objects are presented in Fig. 10. Since this paper is not concerned with the optimization process, let us assume that the result of a dynamic site planning is as presented in Fig. 10b. Since a dynamic layout is represented here in a single drawing, as expected, a number of objects appear to have overlaps with each other. However, review of the object schedule (Fig. 1) will clarify that these are only illusory overlaps.

Representing the dynamic layout from Fig. 10b in a series of 2D drawings using the methods proposed by Rad [40] and Zouein [41] yields the drawings in Fig. 11a and b, respectively. Rad [40] recommended the use of fixed time intervals. As indicated, the drawback of this approach is that it cannot be guaranteed that there will be no illusory overlaps. For example, Fig. 11a shows the result of this approach when a time interval of three (3) months is selected. Although this is a relatively short time interval, the result still includes an illusory overlap in the fourth drawing (4th time interval: months 10 to 12).

The method proposed by Zouein [41] has overcome this drawback by adding a new layout drawing at every instance where a new object arrives at the site (Fig. 11b, Also see Fig. 1 for schedule). Although this method will not contain any illusory overlaps, it will result in an unnecessary large number of layout drawings. The method proposed in this paper will produce 2D layout representations without illusory overlaps, and in a smaller number of documents (Fig. 12).

To present the dynamic layout of Fig. 10b in 2D using the proposed method, first the order in which objects arrive at the site are considered: A–D–B–C–G–F–H–E–I (see Fig. 1). Starting from the first object that arrives to the site and moving forward from the schedule presented in Fig. 1, objects A, D, B, C, and G are plotted on the first layout drawing (Fig. 12). The next object arriving to the site, F, will have an overlap with A and B if plotted in the same layout. It should be emphasized that this is only an illusory overlap since when optimizing the dynamic plan it is already ensured that objects do not have time–space overlaps. To avoid having objects with illusory overlaps, the time interval of the first drawing ends when F enters the site (month 6), and a new layout drawing starts at that point in time. On the new layout drawing, first all the objects from the first drawing that remain to exist on the site beyond the 6th month of the project (i.e. object C, D, and G), are plotted in their known locations on the second layout drawing (see Fig. 1 for objects schedule). Then the object causing the illusory overlap (object F) is added to this new layout drawing. Continuing to the next objects, adding object H will cause an illusory overlap with object G (Fig. 12). Therefore, the third partial layout is generated at month 11. The continuing objects from the second layout (i.e. D, C, F), the overlapping object (i.e. H), and the remainder of objects (i.e. E and I) will be plotted on the third layout drawing.

It should be noted that these layout drawings should not be taken as object *schedule*, but just the layout of the objects on the site. Similar to

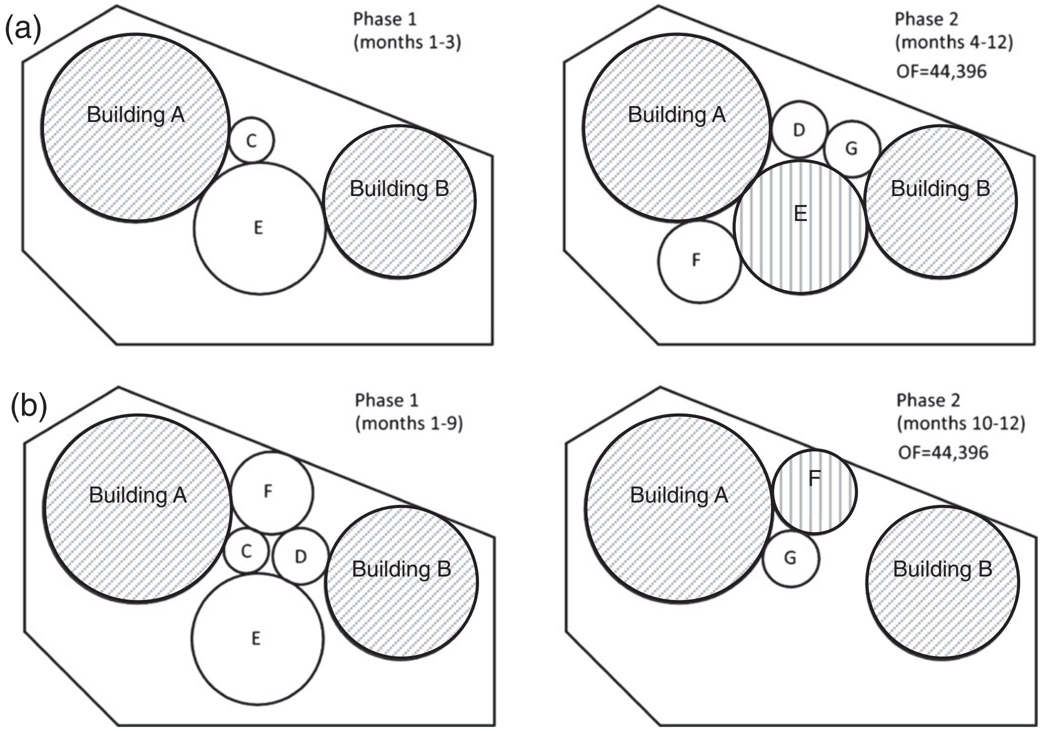


Fig. 7. Alternative phased layouts by dividing the duration at: a. month 3 and b. month 9.

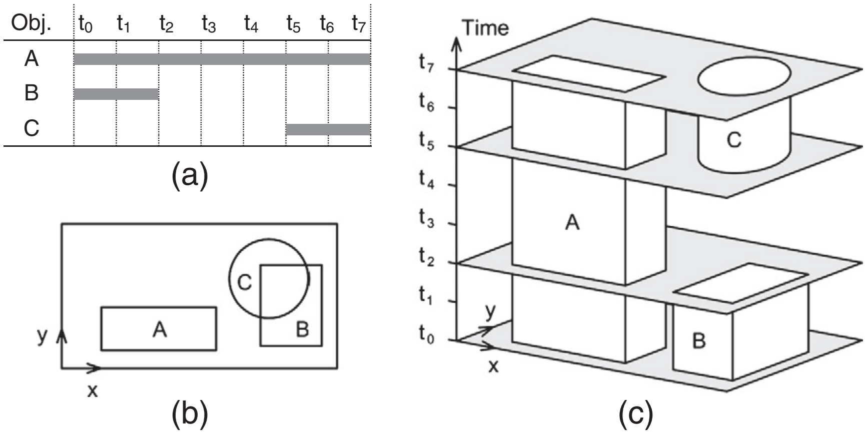


Fig. 8. Time–space presentation: a. objects' schedule, b. 2D view, and c. extruded view.

Zouein's method, in the proposed methodology the objects appearing in a layout drawing do not necessarily exist on the site for the *entire* duration of that layout. For instance in Fig. 12, although object C appears in the last layout drawing that represents the time period between months 11 to 18, it is required only until month 12 (see Fig. 1). This is also the case for the Zouein's method (see Fig. 11, layout drawing related to months 11–14). The advantage of the proposed method, however, is that it presents the dynamic layout in fewer 2D drawings than the Zouein's method (3 drawings versus 7 drawings in the case of this example).

5. Summary and concluding remarks

The time dimension is one of the most influential factors in the optimization of a construction site layout, which defines the way in which the changes that occur on a construction site over the course of a project are reflected. In previous studies, models were referenced under two groups of static and dynamic based on whether or not they considered changes over time in the optimization process. This paper provided a quantitative comparison of different time modeling approaches, and the impact they will have on the generated layout. In particular, the

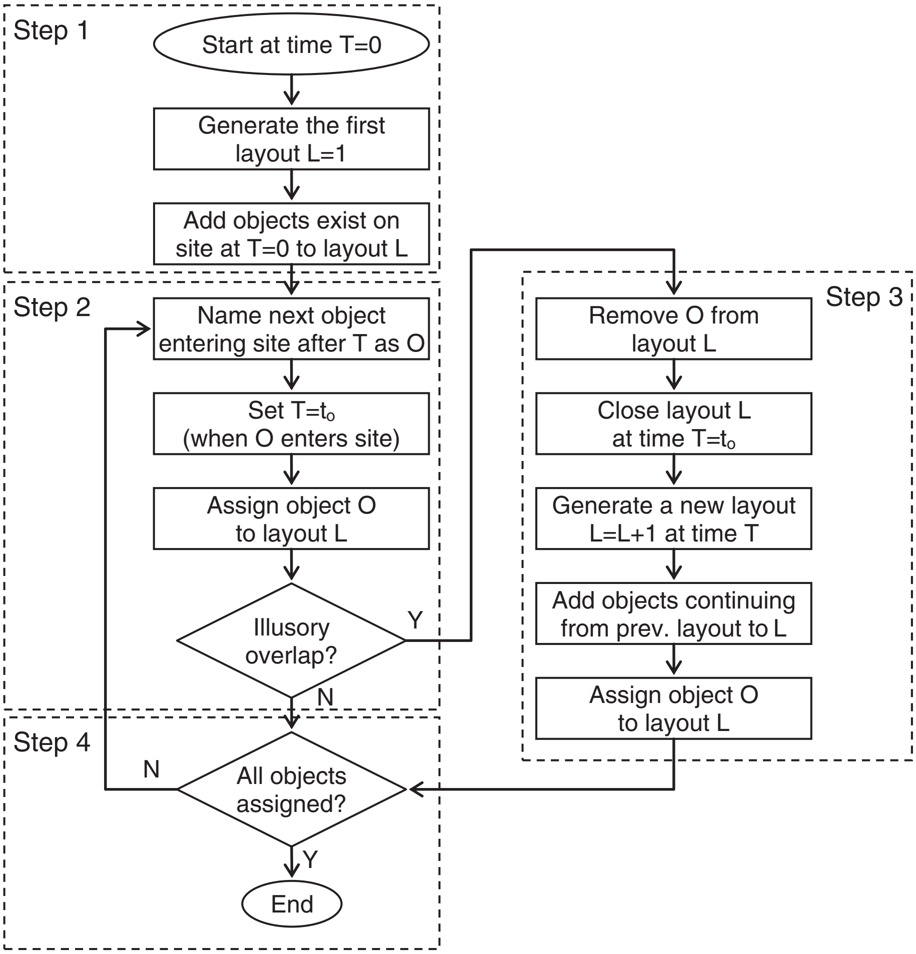


Fig. 9. Flowchart of the proposed algorithm.

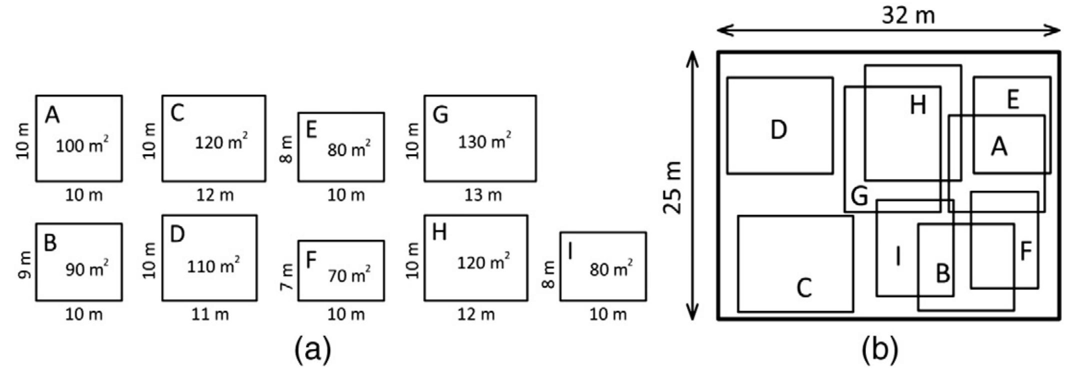


Fig. 10. Dynamic layout for the example presented in Fig. 1: a. Objects dimension, b. Assumed optimized layout.

results show that among the approaches that were previously grouped under the general term "dynamic layout planning", there are in fact two distinct approaches of *phased* and *dynamic* layout planning. Although both approaches take into consideration changes over time, they are in fact very different in their assumptions, and as a result, in the site layout they generate.

The paper demonstrated that the difference between the three approaches of *static*, *phased*, and *dynamic* layout planning stems from the assumptions made under each approach regarding the *site space requirements* over the course of time (time–space requirements). Since the static approach does not consider the changes that occur on the site over time, it leads to a high level of space over-allocation, resulting in an inefficient use of space in the final layout. The phased approach offers an improvement over the static approach in terms of over-allocation of the space. However, since it does not reflect the changes *within each phase*, it still does not allow the most efficient use of site space in the final layout. In the dynamic approach, space is allocated to objects exactly for the duration they are needed. This allows the reuse of the same space by objects that are not on the site at the same time. As a result, the dynamic approach leads to the most efficient layouts in relation to the defined objective function.

The phased approach has another disadvantage compared to the dynamic approach, in that the *order* in which phases are optimized, as well as the *durations* selected for the time intervals, can have an impact on the final outcome — i.e. the generated layout. Even assuming the best order and durations for phases, the sum of a number of optimized partial layouts does not necessarily result in a layout that is optimized over the duration of the project. Finally, this paper presented an efficient method for representing a 4D dynamic site layout in a series of consecutive 2D layout documents for day-to-day usage on the construction

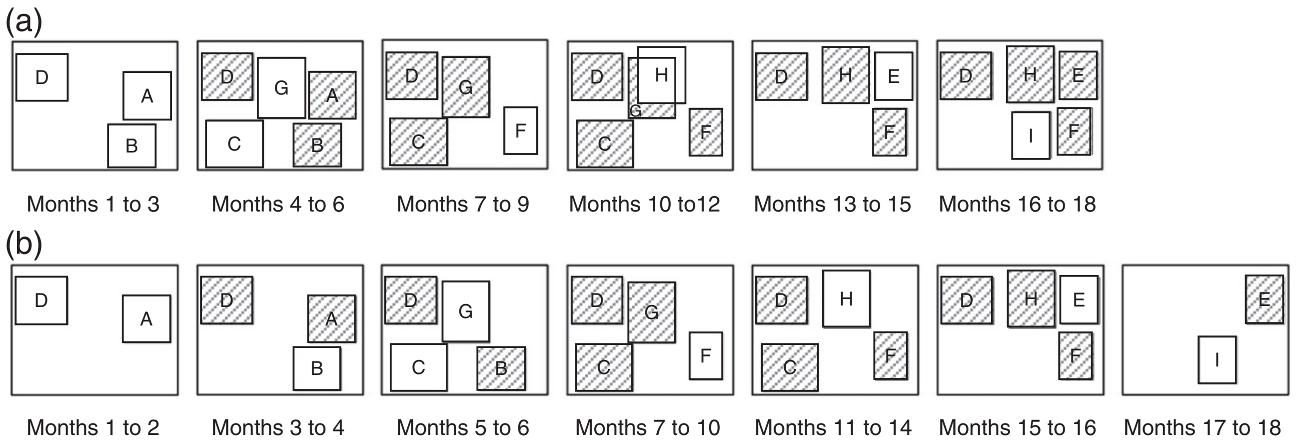


Fig. 11. Representing a dynamic site layout in 2D drawings: a. According to Rad [40], b. According to Zouein [41].

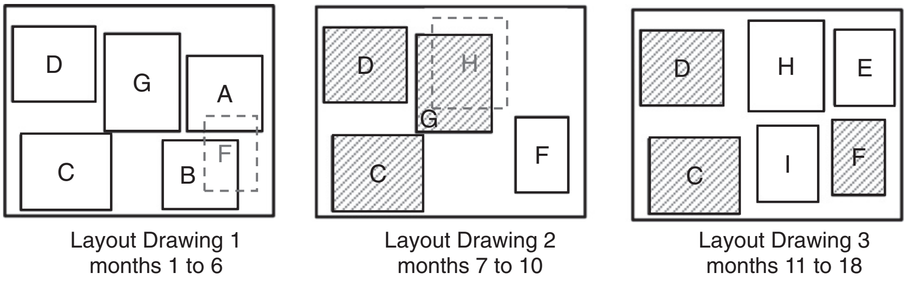


Fig. 12. Representing the dynamic site layout in 2D drawings using the proposed method.

site. The advantage of the presented method over the previously proposed methods is that it allows the representation of a dynamic layout, in minimum number 2D documents without containing any illusory overlaps.

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