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ARTICLE

The constructs of site layout modeling: an overview

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Abstract: The efficient planning of site space through the course of a construction project is referred to as site layout planning. Due to its impact on safety, productivity and security on construction sites, several site layout planning models have been developed in the past decades. These models have the common aim of generating best layouts considering the defined constraints and conditions. However, the underlying assumptions that were made during the development of these models seem disparate and often implicit. This study provides an overview of the existing models and aims to draw a holistic view of variables that have been considered at different levels of detail and using different approaches in the site layout literature. Through close examination and comparative analysis of existing models, this study identifies the components that need to be considered for site layout modeling, referred to as constructs. Possible approaches that can be used to realize each construct are presented, and the advantages and disadvantages of these approaches are discussed. It is hoped that this study contributes to a better understanding of site layout modeling, and provide an outline for the development of new site layout planning models.

Key words: construction site planning, site layout modeling, modeling constructs, site management, optimization models.

Résumé : La planification de l'agencement d'un espace défini dans le cadre d'un chantier de construction est appelée « plan d'aménagement de site ». En raison de l'impact de ce dernier sur la sécurité, la productivité et la sûreté des sites de construction, de nombreux modèles de plans d'aménagement de site ont été développés au cours des dernières décennies. Ces modèles ont pour objectif commun de concevoir des aménagements optimaux en tenant compte de contraintes et de conditions précises. Cependant, les hypothèses de base émises lors de l'élaboration de ces modèles semblent nombreuses et souvent implicites. La présente étude fournit un aperçu des modèles existants et a pour but d'offrir une vision globale des variables qui ont été étudiées à différents niveaux de détail et sous diverses approches dans la littérature traitant de l'aménagement de site. Grâce à un examen attentif et à une analyse comparative des modèles existants, le présent article identifie les composants, nommés « structures », à prendre en compte dans la modélisation de l'aménagement de site. L'article décrit également les différentes approches pouvant être adoptées pour créer chaque structure ainsi que les avantages et désavantages de ces approches. Il est à espérer que la présente étude contribuera à une meilleure compréhension de la modélisation de l'aménagement de site et constituera un point de départ à l'élaboration de nouveaux modèles de plans d'aménagement de site. [Traduit par le Rédaction]

Mots-clés : plan de site de construction, modélisation d'aménagement de site, structures de modélisation, gestion de site, modèles d'optimisation.

1. Introduction

Site space is considered a limited resource in construction projects, besides materials, equipment, labor, time, and money (Tommelein and Zouein 1993). Efficient use of site space can have a significant impact on the productivity, safety, and security on the site, which in turn can affect the cost and schedule of the project. The front-end planning of the layout of construction sites, referred to as *site layout planning*, has received the attention of researchers in recent decades. Site layout planning has close interaction with other construction management processes such as planning, scheduling, and cost estimating (e.g., to determine the required objects, identifies the available space and existing obstacles on the site). Failing to plan the layout of construction sites can lead to unproductive projects, additional material handling and relocation costs, and schedule delays (Tommelein et al. 1992*a*; El-Rayes and Khalafallah 2005).

Due to the complexity and the large number of variables involved, computers were used in developing site layout models from its early years in the late 1980s (Sadeghpour et al. 2004*a*). While these models seemingly all address the same objective of determining the optimum arrangement of objects on a construction site, a quick review of site layout models can reveal that they are actually widely spread in terms of scope and underlying assumptions. Existing site layout studies not only vary in their methodology to generate a *solution*, which is expected for the novelty of the research, but they also differ in how they define the site layout *problem*. Since there are a large number of variables involved in site layout modeling, and since existing studies differ largely in what they include and how they model them, the literature can seem widely spread. For example, as it stands, it can be difficult to identify where each model stands in relation to other models, i.e., how similar or dissimilar they are. It is not accidental that numerical examples are rarely taken from one study and solved with a model developed in another study.

The objective of this study is to render a holistic view of the variables that can be considered in site layout modeling. These variables, referred to as *constructs* in this study, are extracted through comparative study of existing site layout models and mapped together to provide an outline for site layout modeling. The study also identifies and classifies possible approaches that can be taken for the realization and implementation of each construct. This outline can provide a template that facilitates the

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comparison of site layout models with different scopes and assumptions — i.e., which constructs have been considered in a model and how they have been addressed. The structure can also be used as a base for developing new site layout models.

2. Comparative study of site layout models

A close examination of the literature on site layout planning reveals that despite the wide range in the scope and underlying assumptions among different studies, a number of core elements and concepts are common between site layout models. The authors have identified common concepts through comparative analysis of site layout studies over the years of their involvement with site layout research. The motivation behind this effort was to verify whether an outline could be defined that represents the constructs for a generic site layout model and encompasses all the existing studies. In the context of modeling, constructs refer to concepts that are used to characterize a phenomenon and describe problems within a domain (March and Smith 1995). As such, a *model* is composed of a set of propositions representing the relationships among the *constructs*. The identification of *constructs* in each domain is essential to developing new models in that domain. This definition of *construct* has been commonly accepted in engineering design and design science (e.g., Buede 2011; Winter 2008) and more recently it has been adopted in construction management literature (e.g., Ahlemann et al. 2013; Bemelmans et al. 2013; Brady et al. 2012; Voordijk 2011).

The main challenge in this study was that the scope and underlying assumptions of site layout models are often not explicitly documented. While the literature pertaining to site layout models generally provides detailed explanation of how the *solution* (i.e., optimum layouts) is generated, the same attention is often not given to defining the scope and underlying assumptions of a model. This called for a closer examination of the literature to extract the constructs from what was implied in the description of the processes used to develop the solution. Table 1 summarizes a survey of site layout models that have been developed from 1987 to date, presented by the identified constructs and approaches used by each specific model to realize these constructs. The research work included here is identified by searching "site layout" and "construction site" keywords in five major engineering databases, namely Compendex, Inspec, Science Direct, Academic Search Complete, and Google Scholar. To ensure diligence, the list of papers that were cited in these studies, as well as the papers that cited them, were carefully reviewed to identify any other possible study on site layout modeling that was not found by the keyword search. It should be emphasized that the scope of the included studies was delimited to those on construction site layout modeling. In addition, with the exception of a pioneering study (Hamiani and Popescu 1988), only models that were presented in peer-reviewed journal papers were included.

Each column in Table 1 depicts one of the constructs that were found to be common among site layouts models — representing the *intersection* area between models. In each column, the approach that was taken by each model to realize that specific construct is identified. As it can be inferred from the table, commonality was also noticed among these *approaches* as well. In the following sections of this paper, the role of the identified construct in site layout modeling is discussed. Each section further discusses the different approaches taken to realize a construct. In addition to what is presented in Table 1, the following sections will also include concepts that are addressed only in a limited number of studies or models, but as will be discussed, can impact site layout modeling. Collectively, these constructs, along with the approaches taken to realize them, are used to define a general structure for site layout modeling that will be presented in Section 8.

3. Modeling the site space

The ultimate objective of site layout planning is to identify the optimum location for objects on the construction site. Therefore, a formal definition of the *site space* is core to any site layout model. The formal definition of space is important for site layout modeling for two main reasons: (1) verification of space availability and (2) referencing specific locations on the site. Three approaches have been used in the literature to represent the site space that will be discussed in this section.

3.1. Predetermined locations

A number of site layout models used a set of *predetermined locations*, with predetermined shapes and sizes, to represent the available space on the site (Yeh 1995; Li and Love 1998; Tam et al. 2001; Mawdesley and Al-Jibouri 2003; Zouein et al. 2002; Li and Love 2000; Zhang and Wang 2008). This approach simplifies the layout planning problem to an *assignment* problem, in which the aim is to determine the best assignment of *n* objects to *n* (or *n* +) predetermined locations. This simplified approach, which is also referred to as "*location allocation*" (Zouein et al. 2002), can be suitable for projects in which the condition and shape of the site limits the available space to a few isolated areas on the site (Fig. 1*a*).

In a more simplistic use of predetermined locations, the size and shape of objects are ignored and it is assumed that the objects can fit in all the predetermined locations (e.g., Yeh 1995; Li and Love 1998; Tam et al. 2001; Mawdesley et al. 2002). In more sophisticated models, predetermined locations can take unequal sizes and shapes. Assigning locations is therefore constrained by the shape and size of objects, making the problem more realistic, and at the same time, more complicated (e.g., Zouein et al. 2002; Li and Love 2000; Zhang and Wang 2008).

Although representing the available space on the site as a number of predetermined locations simplifies the search process in site layout, at the same time it decreases the flexibility of the model. It limits the application of the model to sites with special conditions, where the actual available space is limited to a number of distinct and isolated locations. For projects with continuous available space, dividing the site into discrete predetermined locations can lead to waste of the site space and to the generation of layouts that are not necessarily the best solution.

3.2. Grid system

Another approach that is commonly used to represent the site space is to divide it into cells using an orthogonal *grid*. In this approach, the position of objects is identified by a unique location reference that is assigned to grid cells (Fig. 1*b*) (Cheung et al. 2002; Hegazy and Elbeltagi 1999, 2000; Elbeltagi and Hegazy 2001; Elbeltagi et al. 2001, 2004; Osman et al. 2003; Khalafallah and El-Rayes 2006*a*, 2006*b*, 2008, 2011; Ning et al. 2010; Yahya and Saka 2014). This approach facilitates the search process and the identification of space conflicts between objects during the search. Unlike the previous approach, the *grid system* enables the possibility of using the entire site space for locating objects.

In a simplistic use of the *grid system*, each object is located in a single grid unit (e.g., Lam et al. 2005, 2007, 2009). Here, the size of the grid unit is selected such that it can fit the largest object. In a more advanced form of grid representation, an object can occupy multiple grid cells (e.g., Elbeltagi and Hegazy 2001; Osman et al. 2003; Ning et al. 2010; Khalafallah and El-Rayes 2011). Using multiple grids allow a more realistic representation of the size of the object in the search process. In addition, it offers the flexibility of examining different shapes and orientations for an object with a fixed footprint, resulting in a more efficient use of space on the site (Fig. 1*b*).

Compared to the *predetermined locations* approach, dividing the site into a *grid* system provides a more realistic representation of the actual site conditions. However, the *grid system* im-

Table 1. A survey of site layout models by their constructs and approaches used to realize the constructs.

Constructs / Models	Site Space			Site Layout Objects			Time Dimension			Planning Goals and Objectives							Search Approach			
				Boundary						Goals			Spatial Relation.							
	Predetermined	Grid System	Continuous Space	Dimensionless	Approximated	Actual Shape	Static	Phased	Dynamic	Productivity	Safety	Security	Closeness	Farness	Containment	Visibility	Construction	improvement	Concurrent	Optimization Technique
Hamiani 1987 Hamiani and popescu 1988			x		x		x			x	x	x	x			x	x			KB
Tommelein et al. 1992b			x		x		x			x			x				x			KB
Cheng and O'Connor 1994			x			x	x			x	x	x	x				x			KB
Yeh 1995	x			x			x			x			x					x		ANN
Li and Love 1998 Li and Love 2000	x			x			x			x			x					x		GA
Zouein and Tommelein 1999			x		x			x		x			x				x			Mth (LP)
Hegazy and Elbeltagi 1999 Hegazy and Elbeltagi 2000 Elbeltagi and Hegazy 2001		x				x[1]	x			x			x					x		GA
Elbeltagi et al.2004		x				x[1]		x		x	x		x	x				x		GA
Tam et al. 2001 Tam et al. 2002	x			x			x			x			x					x		GA
Zouein et al. 2002			x		x		x			x			x					x		GA
Cheung et al. 2002	x			x			x			x			x					x		GA
Mawdesly et al. 2002 Mawdesley and Al-Jibouri 2003	x			x			x			x	x		x					x		GA
Osman et al. 2003		x				x[1]	x			x			x					x		GA
Jang 2004		x		x			x			x			x					x		GA
Sadeghpour et al. 2004a Sadeghpour et al. 2006			x			x	x			x	x	x	x	x	x	x	x			GR
Lam et al. 2005 Lam et al. 2007 Lam et al. 2009		x		x			x			x	x		x					x		AC
El-Rayes and Khalafallah 2005			x		x		x			x	x		x	x				x		GA4
Khallafallah and El-Rayes 2006a Khallafallah and El-Rayes 2006b Khallafallah and El-Rayes 2008 Khallafallah and El-Rayes 2011			x		x		x			x	x	x	x	x	x			x		GA
Easa and Hossain 2008			x		x		x			x			x						x	Mth (NL)
Zhang and Wang 2008	x			x			x			x			x					x		PSO
Sanad et al. 2008		x				x[1]	x			x			x					x		GA
El-Rayes and Said 2009		x			x			x		x			x					x		ADP
Zhou et al. 2009			x		x		x			x			x					x		GA
Ning et al. 2010 Ning et al. 2011		x			x			x		x	x		x					x		AC
Lien and Cheng 2012	x			x			x			x			x					x		PSO
Xu and Li 2012	x			x				x		x	x		x	x				x		PSO
Andayesh and Sadeghpour 2013a			x		x				x	x	x		x	x					x	MTPE
Yahya and Saka 2014		x			x			x		x	x		x	x				x		BCA

Note: KB, knowledge based; ANN, annealed neural network; GA, genetic algorithm; Mth (LP), mathematic optimization (linear programming); GR, geometric reasoning; AC, ant colony optimization; Mth (NL), mathematic optimization (non-linear programming); PSO, particles swarm optimization; ADP, approximate dynamic programming; MTPE, minimum total potential energy; BCA, bee colony algorithm.
[1]The actual shape is reflected by grids.

poses two limitations. First, the representation of the objects' shape will be limited by the orthogonal lines of the grid. As a result, it cannot represent the actual shape of objects with curves or non-orthogonal boundaries in the search process. Second, in the search for the optimum locations, possible locations in between the grid lines might be overlooked. For instance in Fig. 1*b*, location B′ will never be examined for object B, even if it results in a better layout. Selecting smaller grid units can help in reducing the impact of these limitations; but at the same time, it increases the total number of grid units, and hence the computation time and effort.

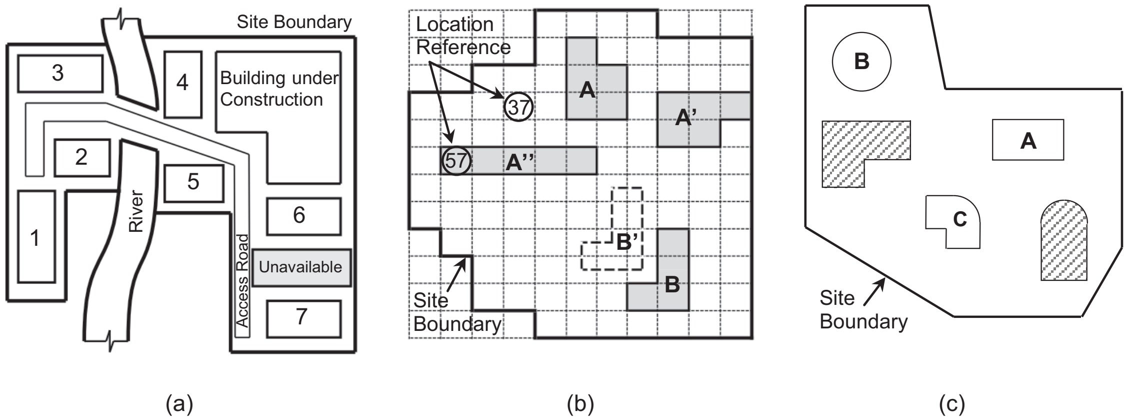
3.3. Continuous site space

In reality, locating objects on the site is not limited to a grid system; objects can be located anywhere on the site that space is available. In a close-to-reality representation of the available space, site space can be modeled as a continuous quantum (Fig. 1*c*) (e.g., Zouein et al. 2002; Sadeghpour et al. 2004*a*, 2004*b*, 2006; Easa et al. 2006; Easa and Hossain 2008; Andayesh and Sadeghpour 2011). This approach offers an increased flexibility by allowing to locate objects anywhere on the site and without being limited to grid lines or predetermined locations. However, compared to the previous two approaches, it makes the search process more complicated and requires more sophisticated algorithms to identify, avoid, and resolve space conflicts between objects.

4. Site layout objects

Site layout objects refer to those that exist on the site for any period of time, and as such, occupy space on the construction site.

Fig. 1. Representing site space: (*a*) predetermined locations, (*b*) grid system, and (*c*) continuous space.



Examples of site layout *objects* are temporary facilities, equipment, materials, and access roads. Certain properties of these objects, namely *typology* (the nature and role of the object), object *boundary* (the shape and size of the object), and *mobility* (the ability of an object to move on the site), will impact the definition of the problem, and as a result, the search process. Out of the above aforementioned properties, object boundary is the one that is most commonly addressed in site layout models (see Table 1 for details). However, some studies have also referred to the importance of the other two. This section provides a description of these object properties and the role they play in a site layout model.

4.1. Object typology

Temporary facilities, construction equipment, material laydown and storage areas, access roads and on-site paths (Mawdesley et al. 2002), workspace, and elements on the site are common types of objects in a typical construction project (Rad and James 1983). The typology of site layout objects is important in site layout modeling as the way they are handled in the layout, and their impact on the required space for operation (e.g., equipment), handling (e.g., material), safety (e.g., roads), or for a combination of these (Thabet and Beliveau 1994). It is therefore important to identify the typology of objects that will be considered in a site layout model.

4.1.1. Temporary facilities

Temporary facilities are structures that support construction crews or activities, such as site offices, trade trailers or guardhouses. Temporary facilities are one of the most commonly addressed object typologies in the site layout literature. In fact, the scope of many of the previous site layout studies is limited to temporary facilities (e.g., Li and Love 1998; Hegazy and Elbeltagi 1999; Elbeltagi et al. 2001; Osman et al. 2003). Temporary facilities are easier to model as their time of arrival is often at the beginning of the project, their shape and size are usually known, and their location often remains unchanged throughout the project.

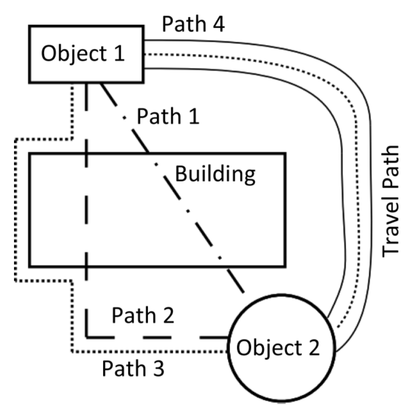
4.1.2. Construction equipment

The location of construction equipment affects the efficiency of the construction activities they are associated with. The space allocated for equipment in site layout planning is not just limited to their physical dimensions, but should also include the space required for operation, as well as a safety (buffer) zone (Al-Hussein et al. 2001, 2005; Moselhi et al. 2004; Hammad et al. 2007; Sadeghpour and Gominuka 2008; Sadeghpour and Teizer 2009; Ning et al. 2011).

4.1.3. Material laydown and storage areas

The location of construction material on the site has a direct impact on the productivity and performance of projects (Thomas et al. 2005). Laydown and staging areas should be selected carefully to avoid double handling and unnecessary movements (Mawdesley et al. 2002), while avoiding underutilization of valuable prime space on the site. Some bulk material such as gravel can take the shape of any available space on site. In addition, their required space decreases over time as they get used up or installed (Zouein and Tommelein 1999).

Fig. 2. Modeling and measuring travel paths between objects.



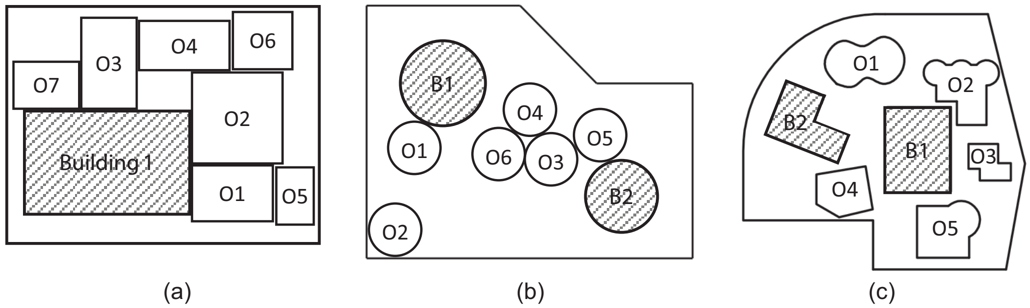
4.1.4. Workspace

Besides the minimum space required for performing the task, additional safety zone should be allocated to the workspaces in the site layout (Akinci et al. 2002). Although the minimum space requirements for different activities are in general known, the shape of their footprint is often more flexible in a layout. This quality renders them as a different object type in the model.

4.1.5. Access roads and on-site paths

Efficiently planned access roads can decrease the time and cost of handling resources, and can improve the safety on construction sites. Despite the recognition in literature of the importance and impact of the efficiency of access roads (Handa and Lang 1988; Mawdesley et al. 2002; El-Rayes and Khalafallah 2005; Sanad et al. 2008), the *planning* of access roads has not yet been addressed in the research to date. The inclusion of access roads in modeling site layouts is important as they define the travel distance between objects — a measure that is often used for the optimality of a generated layout. In existing models, the distance between objects is commonly measured in a simplified manner; either as the rectilinear distance between objects — similar to path 1 in Fig. 2 (e.g., Zouein and Tommelein 1999; Mawdesley et al. 2002; Zouein et al. 2002; El-Rayes and Said 2009) or as the direct Euclidean distance — similar to path 2 in Fig. 2 (e.g., Li and Love 1998; Elbeltagi and Hegazy 2001; Osman et al. 2003; Easa et al. 2006; Andayesh and Sadeghpour 2013*a*). Neither of the two methods takes into

Fig. 3. Modeling object boundary: (*a*) approximate geometry — rectangular shapes, (*b*) approximate geometry — circular shapes, and (*c*) actual shape.



consideration the need to circumvent obstacles (e.g., path 3 in Fig. 2). In reality, the distance traveled between two objects is measured based on the actual paths that are defined on the site (e.g., path 4 in Fig. 2).

4.1.6. Site objects

Site objects refer to those that are *part of the site*, such as natural elements (e.g., trees) and existing buildings. Therefore, the shape and location of site objects on the site are known — and often fixed — during the project. However, they could have a spatial relationship to other objects, and hence impact the location assigned to these. For example, an existing structure could be used as storage for other objects. In addition, the space that site objects occupy on the site will have to be deducted from the available site space (Sadeghpour et al. 2004*c*, 2006). Therefore, it is important to accurately represent the location and properties of site objects in the site layout model.

4.2. Object boundary

Besides object typology, when searching for the optimum site layout, a formal definition of object boundaries (size and shape) is required to determine the space required to accommodate objects, and to avoid space conflicts between them. This section summarizes three different approaches commonly taken by existing models to reflect the 2D boundaries of site layout objects.

4.2.1. Dimensionless objects

In this approach, objects are represented as a point, without a dimension or shape (e.g., Yeh 1995; Li and Love 1998; Tam et al. 2001; Mawdesley et al. 2002). This representation is sufficient for location allocation problems, in which site space is represented as a set of predetermined locations on the site (see Fig. 1*a*). Since the possible locations in this approach are predetermined, the shape and size of objects will not play any role in finding the optimal location for the object. For the same reason, there will be no need to verify overlaps or space conflicts between objects. Although this representation simplifies the computational efforts, its application is limited to projects with predetermined locations on the site.

4.2.2. Approximate geometry

In this approach, the actual shape of an object is approximated by a basic 2D or 3D geometric construct (such as rectangle or cylinder) that circumvents the actual geometry of the object. This is the most commonly used approach in previous studies (e.g., Zouein et al. 2002; Moselhi et al. 2004; El-Rayes and Khalafallah 2005; Easa et al. 2006; Hammad et al. 2007; Easa and Hossain 2008; El-Rayes and Said 2009; Ning et al. 2010; Khalafallah and El-Rayes 2011; Andayesh and Sadeghpour 2011, 2013*a*) (Fig. 3*a* and 3*b*). It takes into consideration the different sizes of objects and is more realistic than the previous approach. In more advanced approaches, the representative boundary (often a rectangle) is allowed to take a rotated position in the layout to improve the flexibility and to make more efficient use of space (e.g., Zouein and Tommelein 1999; El-Rayes and Said 2009; Zhou et al. 2009).

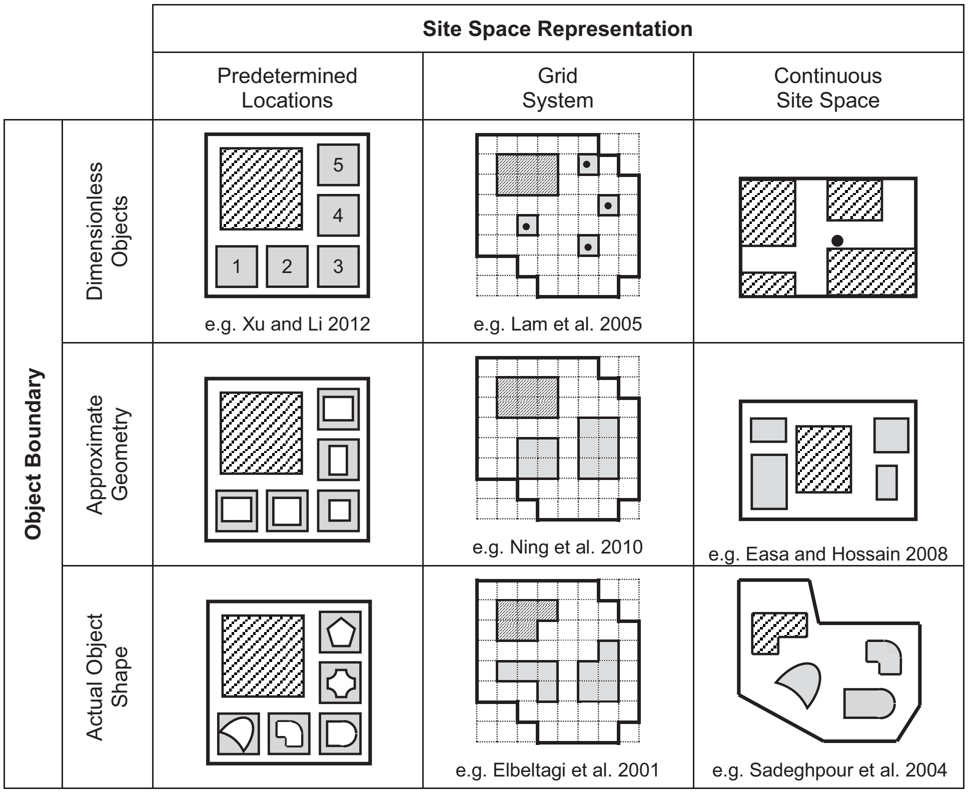
Compared to a realistic representation of an object boundary, using the geometric shape requires less computation and analysis during the search process. For example, identifying overlaps and resolving space conflicts between objects is less onerous since a reduced numbers of vertices and faces has to be taken into account. In sites with very tight space, such as those in urban areas, representing the actual shape of the objects with their simplified circumventing geometry can lead to an inefficient use of the space since the circumventing shape takes up more space than the actual object.

4.2.3. Actual object shape

Representing objects with their actual shape in 2D or 3D enables a more realistic representation of the availability of space on the site, and of locating scenarios. However, it adds to the complexity of calculations. An accurate representation of site layout objects becomes essential for construction sites that are tight in space, such as those in congested urban areas, where even a small available space is of value and should be used efficiently. When a *grid system* is used to represent the site space (see section 3.2), several grid cells can be used to define a close approximation of the object boundaries (e.g., Elbeltagi et al. 2001; Hegazy and Elbeltagi 1999; Osman et al. 2003) (Fig. 1*b*). When representing the *actual shape* of objects is used in conjunction with *continuous* site space representation (Fig. 3*c*), more sophisticated algorithms are required to recognize and resolve space conflicts (e.g., Sadeghpour et al. 2004*a*, 2006). Figure 4 provides a visual illustration for possible combinations of various site space and object boundary representation.

It should be noted that in reality, site layout objects have three physical dimensions (3D), which can also change over time and with the progress of construction, rendering them 4D objects — e.g., the structure under construction. However, so far, in terms of the three physical dimensions, the existing site layout planning models are only able to either consider the 2D or 2.5D (2D with a fixed height in *z* axis) objects. Even though some site layout studies have used the term 4D planning to describe their models, in reality they are “2.5D + Time”. Although eliminating the 3rd dimension, or considering it as a fixed value simplifies the layout planning process, but it can result in unrealistic site layouts that contain space conflicts or safety issues, especially in cases where the dimension of objects change over the time (for example consider the changes to a structure under construction and the movements of a tower crane). In this regard research in site layout planning can benefit from a large body of existing literature on 4D visualization and 4D planning in construction management (e.g.,Staub-French and Khanzode 2007; Hartmann et al. 2008).

Fig. 4. Possible combinations for site space and object boundary representation approaches.



4.3. Object mobility

Objects on construction sites differ in their mobility. Some objects are *stationary* and cannot be moved or relocated. Other objects are *movable* and can be relocated if necessary. Yet other objects perform their roles by *moving* on the construction site. Each of these objects requires different modeling considerations, and therefore, it is important that the *mobility* of objects be defined in their attributes.

4.3.1. Stationary objects

Stationary objects, such as tower cranes and batch plants, have a fixed position for their entire duration on the site. Once located, these objects either cannot be relocated, or are not desired to be relocated. This could be, for example, due to impracticality or a significant cost and time involved in their relocation (El-Rayes and Said 2009). Stationary objects might exist on site for the entire duration of the project or a portion of it. However, the model does not need to search for alternative locations for them once they are positioned.

4.3.2. Moveable objects

Moveable objects refer to those that operate in a fixed position, but can be relocated if required. Some examples of such instances are when a newly arrived object with higher priority needs to take the location of an object of lesser importance; when a better location for an object becomes available; or when there is a change in workflow with other objects over the course of a project. For instance, a concrete testing laboratory facility might have a large workflow with the buildings under construction earlier in the project than at later stages. Therefore, it is located close to the construction area in the early stages of the project (e.g., earthmoving) to reduce travel costs, but can be relocated to a more distant location afterwards, to free up the prime space for objects with more interaction with the construction area. To reflect the additional costs of relocating an object, the inclusion of a *relocation cost* or *penalty cost* can be considered in the objective function of site layout models (Zouein and Tommelein 1999; El-Rayes and Said 2009; Ning et al. 2010).

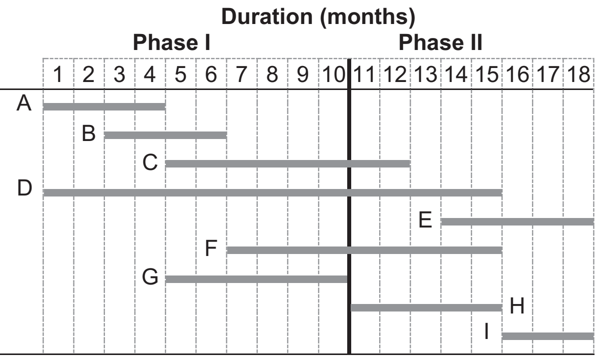
4.3.3. Moving objects

Some construction site objects, such as trucks or earthmoving equipment, perform their task by *moving* on the site. Determining the space requirements for these objects and modeling them in site layout planning is more complicated than for stationary or movable objects. This is due to the fact that their space requirements can vary largely based on the activity they perform (Tommelein and Zouein 1993). Although *moving* objects require space on the site, they do not occupy a fixed position. Instead, they require routes (e.g., trucks) or operation zones (e.g., excavators). In addition, it is important to consider the safety buffer zone around the working areas and moving areas of these objects to decrease the chances of accidents and injuries on construction sites (Riaz et al. 2006). Some studies have investigated space requirements for the safe operation of moving objects (e.g., Al-Hussein et al. 2005; Zhang et al. 2005; Sadeghpour and Gominuka 2008; Sadeghpour and Teizer 2009). However, the incorporation of these requirements into site layout modeling has not been addressed yet in research. Most existing site layout models consider only the optimization of the location of *stationary objects*. Including *movable* and *moving* objects in the optimization will make a model closer to the reality of a construction site, but it also adds to the complexity of computations and analysis in the layout planning process. Determining the space available for the maneuver of a moving object in a confined space (referred to as Configuration Space or C-Space) has been studied extensively in motion planning in robotics and can be adopted for construction site layout planning (Andayesh and Sadeghpour 2014*a*; Choset et al. 2005).

Due to capabilities of building information modeling (BIM) in managing object-based information, some studies have suggested the use of BIM to manage site layout objects and their properties for site layout planning (Zhang and Hu 2011; Hu and Zhang 2011;

Table 2. Schedule and duration of objects in a sample construction project.

ID	Object	Size (grids)	Workflow with Bldg.
A	Geotechnical lab.	2×2	20
B	Rebar workshop	2×2	20
C	Batch Plant	3×3	35
D	Offices	3×3	30
E	Carpentry	2×3	35
F	Storage	3×3	25
G	Gravel depot	2×3	15
H	Bricks depot	2×3	30
I	Landscape workshop	2×2	15



Sulankivi et al. 2009; Chau et al. 2004). As BIM facilitates managing the information on site space and object dynamics, it can serve as a suitable implementation platform for site layout planning models. Using BIM as a platform to manage objects can also facilitate the integration of site layout planning with other applications of construction management such as scheduling, labor management, and supply chain management.

5. Modeling the time dimension

As the construction project progresses and activities change, the required construction objects that are present on the site (such as material, equipment, and supporting facilities) are subject to change as well. The importance of incorporating the changes that occur over the time in construction projects has been emphasized in different areas of construction management literature such as scheduling, progress monitoring, BIM, 4D visualization, and resource planning (e.g., Ma et al. 2005; Hammad et al. 2007; Russell et al. 2009). These studies aim to reflect the dynamic nature of construction sites for developing more realistic models. The focus of this section is to illustrate how the time dimension is addressed in site layout planning research and discuss the approaches taken by the existing models to reflect the changes over time in site layouts. In the context of site layout planning, those changes that are relevant to the occupation or usage of the site space are of importance. For example, when construction materials get consumed or installed, they no longer occupy site space. As a result, space is freed up for new objects that arrive to the site. These changes will create different space requirements on the site at different periods of time. Three approaches — *static, phased*, and *dynamic* — have been used in previous studies to represent the time–space changes in site layout planning. These approaches and their differences will be discussed in this section. A numerical example is used to demonstrate the differences between the three approaches in the context of site layout planning.

5.1. Static site layout planning

Inspired by industrial plant layout planning, early studies of construction site planning defined it as a *static* problem (e.g., Hamiani 1987). While there are a large number of similarities and dissimilarities between site and plant layout planning (see Isaac et al. 2012 for detailed comparison), static planning does not take into account the changes that occur on the construction site over the course of time. In other words, it is assumed that all objects exist on the site for the entire duration of the project. This assumption is clearly a simplification of the dynamic nature of construction sites (Tommelein and Zouein 1993; Zouein 1996; Sadeghpour et al. 2005). Static models can be practical when there are few changes that occur on the site, and the available space is abundant, such as in short-term projects with few objects and a large construction site (Andayesh and Sadeghpour 2012).

Objects on the site are typically required for only a limited period of time during the project — a time referred to as the object's *lifetime* or *service time*. When an object is no longer required, its space becomes available for new objects arriving at the site. Since static layouts do not consider the actual lifetime of the objects, they do not allow reuse of space on the site (Zouein and Tommelein 1999; El-Rayes and Said 2009). While the static approach simplifies the complexity of the problem, in projects with long durations and limited space, ignoring the possibility of reusing space can lead to layouts with space conflicts or inefficient layouts.

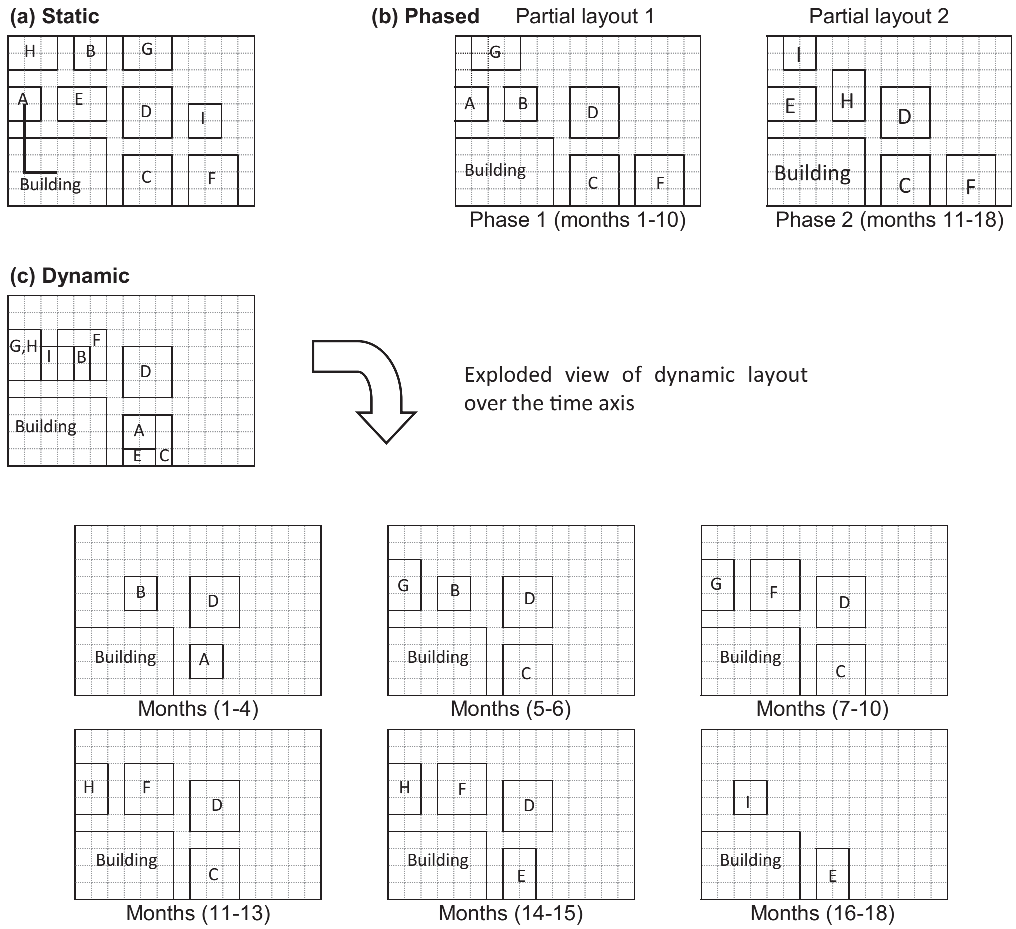
5.2. Phased site layout planning

To reflect changes on the construction site, in the *phased* approach the project duration is divided into several time intervals. A separate layout, referred to as *partial layout*, is generated for each time interval (e.g., Rad 1980; Tommelein and Zouein 1993; Elbeltagi et al. 2001). In this approach, the changes in the required site space are reflected through changes allowed from one partial layout to another. Partial layouts for each time interval are usually generated in chronological order and are often optimized separately considering only the objects required for that specific time interval (e.g., Zouein and Tommelein 1999; Elbeltagi et al. 2001, 2004; Xu and Li 2012; Yahya and Saka 2014). If an object's lifetime extends across several partial layouts (e.g., Batch plant, Offices, and Storage), it is often considered as a fixed object in the latter layouts, with the location identified for it in the earlier partial layout (see Table 2). However, some phased layout models allow the location of objects to change from one partial layout to another to reflect the possibility of changes on construction sites (e.g., Zouein and Tommelein 1999).

Phased layout planning provides an improvement over static planning in taking the changes on the construction site into consideration. However, in phased planning it is still assumed that in each phase objects are required for the entire time interval of the partial layout developed for that phase (e.g., El-Rayes and Said 2009). This can prevent effective use of site space as it prevents the reuse of site space as it becomes available in the middle of a phase. For instance, in the project depicted in Table 2, the project duration is divided into two time intervals, i.e., from month 1 to month 10, and from month 11 until the end of the project, month 18. In this example, Geotechnical lab (object A) and Batch plant (object C) do not have any time overlap, but since they are in the same time interval, they cannot be assigned to the same location in the *phased* approach.

Partial layouts in the *phased* approach are often optimized in chronological order. As a result, those generated for the later phases are highly influenced by those generated earlier. To overcome the effect of order of generating partial layouts, one study proposed to move back and forth between partial layouts to iteratively improve them (El-Rayes and Said 2009; Said and El-Rayes 2013). However, the dependency between the partial layouts still makes it very challenging, if not impossible, to achieve a set of

Fig. 5. Site layouts generated using different time modeling approaches for the same project: (*a*) static layout, (*b*) phased layout, and (*c*) dynamic layout.



layouts that are collectively optimized over the duration of the project.

5.3. Dynamic site layout planning

Dynamic site layout planning was a term coined by Tommelein and Zouein (1993) to refer to the representation of changes on the construction site in site layout planning. Since then, the term "dynamic" has been used in different senses, to reflect the inclusion of the time factor in site layout planning (rendering it a *dynamic* term!). To reflect the progress that has been made in research, this paper differentiates between *phased* layouts (which use a simplified approach to reflect changes over time) and fully dynamic layouts. Two time-related properties characterize *fully* dynamic site layout planning, as defined in this paper: (1) layouts are collectively optimized over the entire duration of the project (4D optimization) and (2) the *actual* changes in the life time of objects on the site are considered in generating layouts.

In this definition of dynamic site layout planning, space is allocated to objects for their actual lifetime on the site (as opposed to allocating space to objects for the duration of a *phase*). In dynamic planning, space allocated for an object can be reassigned to other objects before its arrival to the site, or after its departure. Such examples show that dynamic models reflect the changes of space requirements more realistically. For instance, in the example illustrated in Table 2, Geotechnical lab (object A) and Batch plant (object C) can occupy the same space in a layout generated in the dynamic site planning approach, while the phased site planning would not allow that. Dynamic site planning, thus, utilizes the available site space more efficiently. In the above example, only four objects compete for the best locations at any given time in dynamic approach, whereas in the phased planning this number will be artificially increased to six, and in the static approach, to nine. Therefore, in the *dynamic* approach objects will have a higher chance of being allocated in better locations.

To demonstrate the impact of different approaches for modeling the time factor, three layouts were generated for the example presented in Table 2 using the static, phased, and dynamic approaches (Fig. 5). Let us assume that the objective in this example is to minimize the total travel distance, represented by workflow × rectilinear distance between the center of each object and the center of the "Building" under construction (Fig. 5), and that objects have to maintain a minimum distance of one grid cell from each other to allow circulation on the site. Figure 5 shows three layouts representing the best solutions for each of the time modeling approaches. In the static layout (Fig. 5*a*), each object will be allocated space for the entire duration of the project (i.e., months 1 through 18). In the phased layout (Fig. 5*b*), space will be allocated to objects A, B, C, F, and G for the entire duration of the first time interval (months 1 through 10), and objects C, D, E, F, G, and H for the duration of the second time interval (months 11 through 18). In the dynamic layout (Fig. 5*c*), objects are allocated space only for the duration that they are scheduled to be on the site (see Table 2 for schedule). For clarity purposes, the dynamic layout (Fig. 5*c*) is presented with a number of layouts using exploded view over the time axis as proposed in Sadeghpour et al. (2005), which should not be confused with the partial layouts in the phased approach. The total travel distance (TTD) for the layouts can be calculated as

$$\text{(1)} \qquad \text{TTD} = \sum W_i d_i$$

where W_i represents the frequency of the workflow from object i to the building (see Table 2), and d_i is the center-to-center rectilinear distance between object i and the building under construction. For example in the static layout shown in Fig. 5*a*, the distance between A and the building is 6 units. Based on eq. (1), the TTD for layouts generated using the three approaches can be calculated as follows:

$$\text{TTD}_{\text{Static}}: 6\times 20 + 9\times 20 + 6\times 35 + 9\times 30 + 5.5\times 35 + 10\times 25 + 12\times 15 + 8.5\times 30 + 12\times 10 = \mathbf{1845}$$

$$\text{TTD}_{\text{Phased}}: (6\times 20 + 5\times 20 + 6\times 35 + 9\times 30 + 10\times 25 + 7.5\times 15) + (5.5\times 35 + 6.5\times 30 + 8\times 15) = \mathbf{1570}$$

$$\text{TTD}_{\text{Dynamic}}: 5\times 20 + 5\times 20 + 6\times 35 + 9\times 30 + 5.5\times 35 + 6\times 25 + 6.5\times 15 + 6.5\times 30 + 4\times 15 = \mathbf{1375}$$

This difference is due to the increase in efficiency of using space over time from static to phased approach and from phased to dynamic approach and demonstrates the main advantage of fully dynamic approach over the phased approach.

The decision on which approach to choose for modeling the time factor is an integral part of modeling a site layout problem. Static layouts simplify the layout problem and can be useful for projects with short time spans, where few changes occur in the space requirements over the course of the project. For more complex projects, with longer durations and numerous changes over the duration of the project, failing to address the impact of time can lead to inefficient layouts with artificial space conflicts or shortages, and unnecessary material handling or relocation costs. Readers who are interested in additional details and numerical examples on the difference between the three approaches are referred to Andayesh and Sadeghpour (2014*b*).

6. Planning goals and objectives

Site layout planning processes are generally guided by certain overarching *goals*. The three goals that are commonly defined in site layout studies are *increasing the productivity*, *safety*, and *security* (Fortenberry and Cox 1985; Handa and Lang 1989; Tommelein et al. 1992*b*). To realize *goals*, they must be translated into tangible *objectives*. In site layout planning, the objectives are expressed by means of spatial relationships between objects. For example increasing the productivity on the site (a goal) can be reached by the minimizing the travel distance between objects (a tangible objective) (e.g., Elbeltagi et al. 2004); the goal of increasing the safety, can be reflected in minimizing the number of road intersections (e.g., El-Rayes and Khalafallah 2005); and the goal of increasing security, can be achieved by maximizing the visibility from the security booth (e.g., Sadeghpour et al. 2006).

While the *objectives* in the existing models are generally well-defined, the *goals* of these models are often not explicitly indicated. It should be noted that a *goal* can be reflected in more than one *objective*. In other words, the relationship between an *objective* and a *goal* is not necessarily a one-to-one relationship. For instance, the goal of "increasing security" can be reached by "reducing the distance between the guard house and the storage" and (or) "making the storage visible from the security booth". Reciprocally, a planning *objective* can address more than one *goal*. For instance the objective of "reducing the distance" between two objects not only can address the goal of increasing security, but it may also reflect the goal of increasing productivity (for example by facilitating the access between objects). In layout optimization, *objectives* are represented through the concepts of *utility function*, *spatial relationships*, *constraints*, and *penalties*. This section discusses how these concepts are commonly used in site layout modeling. It should be noted that these terms have been, at times, used in different senses in the site layout literature. In an effort to address occasional differences, this paper adopts the use of these terms according to their accepted definitions in the optimization literature (e.g., Marler and Arora 2004), which is in line with the majority of the site layout literature.

6.1. Utility function

In planning for the layout of a construction site, often the goals of increasing safety, security, and productivity need to be addressed simultaneously. As a result, site layout models often consider multiple objectives in searching for an optimum layout. A *utility function* is the mathematical representation of a number of *objectives* in a single function (Marler and Arora 2004). (Note: in the existing site layout literature the term Objective Function is also used alternatively for the Utility Function). The objectives defined for a model may be at times contradictory and have an opposing impact on the final location of objects. For example, locating labor welfare facilities near the construction area increases productivity by minimizing the travel time, but at the same time, a safety related objective may aim at maximizing this distance. To reflect the relative importance of different objectives in multi-objective models and achieve a single solution, *weights* are commonly assigned to each objective (Marler and Arora 2004).

For example, to "minimize travel distance" between different pairs of objects, the *utility function* can be defined as the total weighted distance between pairs of objects:

$$\text{(2)} \qquad \text{Utility Function}_{\text{min.dist.}} = \sum W_{ij} d_{ij}$$

where W_{ij} is the weight reflecting the importance of the closeness between objects i and j. The weight represents the relative importance of the closeness between pairs of objects for the decision maker, and could be based on, for example, the cost or frequency of travel between them. The utility function is then used to identify an optimal solution for the planning problem through an *optimization technique*. The degree to which different solutions satisfy the defined objectives can be measured with the value they achieve for the utility function. The example of using the utility function was used in the case example in Section 5.3. The utility function in eq. (2) is also employed in a large number of the existing site layout studies such as Li and Love (1998), Zouein and Tommelein (1999), Elbeltagi et al. (2001), Osman et al. (2003), Zhang and Wang (2008), Andayesh and Sadeghpour (2013*a*).

6.2. Spatial relationships

The objectives of a site layout model involve, explicitly or implicitly, a definition of *spatial relationships* between objects (Tommelein 1991). For example, for the objective of "minimizing travel distance" between two objects, a "*closeness*" relationship is in fact delineated between those objects. Most of the existing site layout models have mainly focused on the objective of minimizing travel distance, and accordingly can only define *closeness* relationships between objects. However, other types of spatial relationships can also be useful in site layout modeling. Examples of such relationships are *farness* (for objects that need to be located far from each other), *visibility* (for objects that need to be in line of sight with each other) or *containment* (when an object needs to be inside or outside an area delineated by the boundaries of another object). For example, a *visibility* relationship could be defined between a valuable material and the security booth; or a *containment* relationship could be defined between a storage area and the reach of a crane. A list of spatial relationships relevant to construction site layout can be found in Sadeghpour et al. (2004*b*, 2004*c*, 2005).

In a multi-objective site layout model (e.g., Tam et al. 2002), it is possible to have more than just one objective between the same pair of objects. For example, two objects may be required to be far from each other, but at the same time be visible to one another. A utility function provides the possibility of mathematically combining different objectives. As such, eq. (2) can be written as a general *utility function* that considers different objectives between pairs of objects:

$$\text{(3)} \qquad \text{Utility function} = \sum W_{ijk} R_{ijk}$$

where R_{ijk} represents a numerical value for the fulfillment of objective k between objects i and j; and W_{ijk} is the weight reflecting the relative importance of that objective. Depending on the spatial relationship used to define an objective, the fulfillment of an objective function can be expressed in binary (e.g., containment: inside/outside) or continuous (e.g., closeness: as distance between objects get closer a better score will be achieved).

6.3. Constraints and penalties

In the context of optimization, *constraints* define a set of feasible solutions, out of which the optimal solution is sought. A feasible solution is one that does not violate any constraint (Marler and Arora 2004). A constraint in site layout planning could be, for example, that the laydown area for a certain material has to be within the reach of the crane. *Penalties* are used to reflect a degree of flexibility regarding the violation of constraints: they do not indicate that a solution is unfeasible, only that it is less desirable. For mathematical representation, penalties are added to the *utility function* when constraints are violated (Marler and Arora 2004). Adding a *penalty* to the *utility function* removes it further away from the ideal score, indicating that the solution is less desirable. As such, the *utility function* in eq. (3) can be written as

$$\text{(4)} \qquad \text{Utility function} = \sum W_{ijk} R_{ijk} + P_{mn}$$

in which P_{mn} represents the cost of penalty m for the nth instance it occurs.

An interesting application of penalties has been in the implementation of the *cost of relocation.* Cost of relocation refers to expenses that can occur if an object is needed, or considered, to be moved during the course of construction from the first location it is assigned to. Relocations are often considered when two objects with time overlaps compete for prime space on the site. For example, if according to the schedule, the object with a lower priority arrives at the site sooner than the object with the higher priority, instead of reserving the prime space for the object with the higher priority until it arrives to the site, it could be decided that the first object will be located in the prime space until the second object arrives at the site, at which point the first can be relocated to open up the prime space for the second object with higher priority. Although this scenario may lead to a reduced total travel distance (e.g., better score for Utility Function), it is important to consider the costs of setup and relocation when making the relocating decision. This cost can be added as a *penalty* to the total score that is calculated for the layout (e.g., Zouein and Tommelein 1999; El-Rayes and Said 2009; Ning et al. 2010). Penalties can also be used to increase safety by adding a P value to the utility function for every occurrence of an unsafe situation. For example penalties have been used to minimize the risk of potential accidents by adding a penalty value for every instance of intersection of onsite paths (El-Rayes and Khalafallah 2005).

The challenge in adding the *penalty* to the *utility function* as shown in eq. (4) is that it is difficult to normalize the variables such that one does not overweigh the others. For example, if the values assigned to the penalty are too large, it may lead to a situation in which the weighted objectives ($W_{ijk}R_{ijk}$) will not have much of an impact on the utility function. Using large values for penalty can, however, be a simple and practical method to implement *constraints*: i.e., to eliminate any solution that does not adhere to the minimal requirements defined for the project. For example, by assigning a large penalty value to a set of predefined unsafe situations will result in the rejection of any solution that contains them.

In closing of this section, it may be worth reiterating that the distinction between the *goals*, *objectives*, *objective–utility functions, special relationships, constraints*, *and penalties* are not always clearly and explicitly defined in the current literature. A clear definition of these constructs is very important for developing future site layout models since they will have a major impact on the direction a model takes to generate layouts. These concepts are also crucial for evaluating the functionality of a model; i.e., whether the output of the model has achieved the goals that were initially defined for it.

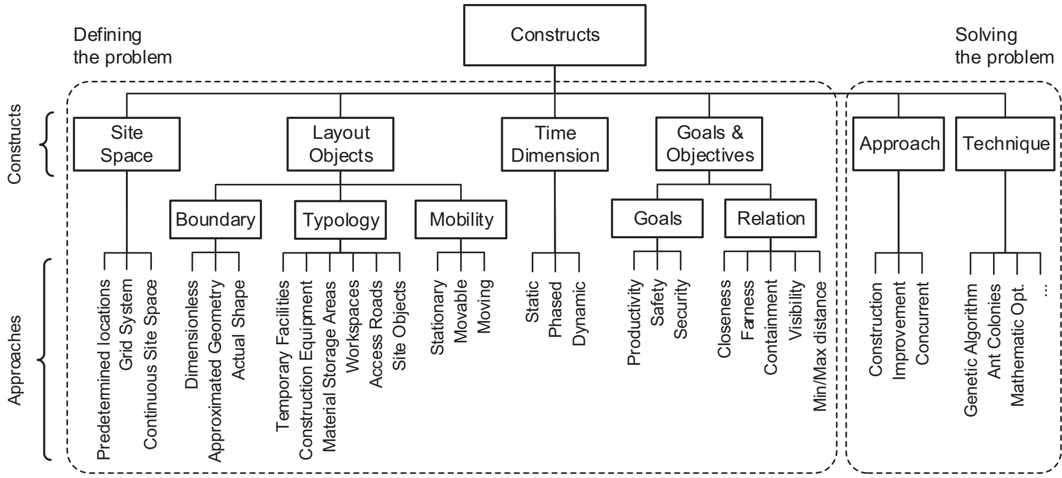
7. Search approach and optimization technique

Once all the elements for the construction site layout problem have been defined, the appropriate *search approach* and *optimization technique* for solving the problem have to be identified. The *search approach* defines *how* and *in what order* the space is allocated to objects. Different *search approaches* have been used in the literature for allocating space to the site layout objects. In the early years of site layout planning research, two search approaches of *construction* and *improvement* were introduced (Moore 1980). A third, *concurrent* approach, has been identified by the authors and introduced in this paper. These three search approaches will be discussed in this section.

An optimization technique is required to implement the selected search approach and identify the optimum solution. A review of advantages and disadvantages of different optimization techniques can be found in Bangert (2012). Existing models have used various techniques, ranging from exact mathematical methods to heuristic algorithms to optimize the defined utility function (see Table 1). However, the optimization techniques that can be used for site layout are numerous and not limited to those that are used in the literature. The choice of *optimization technique* is affected by how other constructs are addressed but mostly intertwined with the *search approach* that is selected for the model. This interconnectivity will be discussed under each *search approach* in this section:

1. Construction approach: In this approach, space is allocated to one object at a time. At each step, the optimum location for only one object is searched, based on the location of objects that have been assigned a location up to that point (e.g., Tommelein et al. 1992*b*; Tommelein and Zouein 1993; Zouein and Tommelein 1999; Sadeghpour et al. 2004*a*, 2006). In this approach the optimum position of an object depends on the arrangement of previously located objects. Thus, the *order* of assigning locations to objects has a significant impact on the final layout. This order is often defined — either by the user or as a default in the model — based on factors such as the cost of relocation, the frequency of interaction with other objects (Zouein and Tommelein 1999) or a combination of weighted factors (Sadeghpour et at. 2004).
2. Improvement approach: In this approach, space allocation starts with an initial layout — often randomly generated — for all objects. The initial layout is gradually improved by changing the position of objects and generating new layouts in consecutive steps. At every step, the newly generated layouts are evaluated against an objective function to identify the fittest layout. This process is continued until no further improve-

Fig. 6. Constructs of site layout modeling.



ment can be achieved, or a set number of iterations have been conducted. Metaheuristic methods such as Genetic Algorithms (GA) (e.g., Tam et al. 2001; Jang 2004), particle swarm optimization (Zhang and Wang 2008; Lien and Cheng 2012), approximate dynamic programming (El-Rayes and Said 2009), ant colony systems (e.g., Lam et al. 2007), bee colony algorithm (Yahya and Saka 2014), and mixed-integer programming (Wong et al. 2010) that have a recursive nature and improves the quality of genes (answers) over several generations (steps) are generally used for implementing an improvement approach. Using the *improvement* approach, close-to-optimum solutions can be generated. However, due to the large number of possibilities at every step and the nature of metaheuristic algorithms, it cannot be guaranteed that the global optimum will be reached.

3. Concurrent approach: In this approach, space is allocated to all site layout objects concurrently, with the aim of finding the global optimum solution. The *concurrent* approach differs from the *construction* approach in that space is allocated to all the objects at once. Similar to the *improvement* approach, the *concurrent* approach allows all objects, regardless of the time they exist on the site, to compete for the best locations concurrently and with an equal opportunity. However, unlike the improvement approach, concurrent approach aims to generate a *single* solution that is globally optimized, as opposed to gradually improving the result towards better layouts. In the improvement approach, several intermediate layouts will be generated that each is slightly better than the previous one. The search is considered complete when a certain threshold in the value of the objective function is met. The layout generated at that point is considered acceptable and as the final answer. The layouts generated immediately before the final layout are only slightly less optimal than the one accepted as the final layout and could have been considered acceptable too, if the threshold was set at a lower value. The *improvement* approach will not necessarily aim to produce the globally optimum solution; instead, it aims to provide a set of close-to-optimum solutions through gradual improvement. In contrast, in the *concurrent* approach there are no intermediate solutions. The concurrent approach aims for a *single* final answer that is globally optimum. An expounding example for the *concurrent* approach is mathematical optimization, in which a number of equations are solved to find the single optimum layout (e.g., Easa and Hossain 2008).

Converging to a solution can be less challenging when the concurrent approach is used for layout problems that are static in nature (e.g., manufacturing plant layout), or are assumed to be *static* (e.g., Easa and Hossain 2008). The implementation of concurrent approach can become more challenging when the *dynamic* conditions of construction sites — in which objects arrive and leave at different times, and in which relationships may also change over the course of time — are taken into consideration (e.g., Andayesh and Sadeghpour 2013*b*).

As the search approach defines the order of allocating space to objects and how optimal the final layout is, the choice of search approach and a compatible optimization technique can clearly have a major impact on the outcome of a model. Construction approach could be sufficient for projects with limited number of objects and limited number of predetermined locations. For larger projects it would be unlikely to achieve an optimum solution using construction approach. For such projects improvement and concurrent approaches are more likely to generate more efficient layouts. The decision of selecting a *search approach* for a site layout model should be based on what level of accuracy and sophistication in optimization is required and expected to be achieved by the model. It is worth noting that the optimization *technique* is only a tool for the implementation of the *search approach*. Therefore, it is important that the optimization *technique* is selected only after the suitable *search approach* is selected, and considering the approaches selected for all the other constructs — not vice versa. In other words, the driving force for selecting the approaches used for each construct should be the level of sophistication that the model needs to meet, and not the capabilities of the optimization *technique*.

8. An outline for the constructs of site layout modeling

The previous sections of this paper described the constructs of site layout modeling. These constructs were identified by extracting the common components from the existing models in the literature. By systematically mapping the constructs that were included in the definition of *different* models, a single outline was generated for the constructs of site layout modeling (Fig. 6). As the *approaches* to address each *construct* in various models were reviewed, it was also noticed that there were commonalities between different models for the approaches used. In other words, for each construct, there were a certain number of approaches that have been used among all the models in the literature. The lower level of the outline in Fig. 6 presents these approaches under each construct. Therefore the outline presented in Fig. 6 presents a conceptual framework of constructs that represents all the models in the literature. A closer look at the outline also reveals that the constructs of the site layout modeling can be clustered into two groups, relating either to the *definition* of the problem in a model, or to the generation of the *solution*. While defining the *goals*, representation of *site space*, *site layout objects*, *time dimension*, and *spatial relationships* are related to the *definition* of the problem in a model, the decision on the *search approach,* and *optimization technique* used to generate the layout are specifically related to how a model generates a *solution*.

Another trend that can be observed at the approach level is that two specific groups can be identified. When the possible approaches under each construct increase in the level of sophistication, and therefore flexibility to accommodate a wider range of site layout problems. For example in representing "Site Space", the *continuous* approach offers more sophistication and flexibility than *grid system*, and *grid system* in turn offers more than *predetermined locations* approach. Besides "Site Space" representation, approaches available for the constructs of "Layout Object Boundary", "Time dimension", and "search approach" are of the same nature. The increased level of sophistication and flexibility is marked with an arrow under each group in Fig. 6. The second group includes those that are not necessarily represented in all the models, but the more of those that are represented, the more flexible and sophisticated the model will be in accommodating site layout problems. For example, under "Layout Object Mobility", stationary objects are often commonly represented in site layout models; but not movable or moving objects. The more mobility types a model can represent, the more flexible it will be in representing a wider range of site layout problems. Besides "Layout Object Mobility", "Layout Object Typology", "Goals", "Relations" constructs share the same nature of *the-more-the-better*. The Optimization Technique does not follow the characteristics of any of these two groups. It will not be possible to prescribe an optimization model over the others. It will have to be selected based on the approaches selected for the previous constructs, especially dependent on the allocation approach selected for the model. To achieve the most level of sophistication and flexibility, a model needs to use approaches on the far right end of the first group, and as many varieties of possible of the second group.

The outline presented here can be used as a guideline in developing new site layout models: it outlines the constructs that need to be addressed and possible approaches that can be taken to address each construct. The outline can also be used for parametric comparison of site layout models and for identifying the similarities and dissimilarities between models. For example, this outline can make it more clear how and in what aspects the model developed presented in (xxx) is different from the one in (YYY), or why an example from one cannot be used in the other one.

This outline was used in developing a new site layout model (Andayesh and Sadeghpour 2013*a*). The outline assisted in a systematic and meditated approach on what constructs were needed to build the model, and what approaches could be taken to address each construct. The aim in developing this model was to provide the most level of flexibility. Therefore it was aimed to use *continuous* approach for Site Space representation, actual shapes for Boundary of Layout Objects, *dynamic* approach for representing the Time Dimension, and *concurrent* for the Search Approach. From the second group of constructs, all possibilities for Layout Object Typology and Mobility, Goals and Relations were considered. Based on the selected approaches it was determined that a mathematical optimization can provide the best optimization technique for the defined model, especially due to the flexibility that can be achieved through mathematical equations, and the desired concurrent approach. After preliminary modeling, the actual shape of objects were replaced by rectangular shape with different sizes and orientations to reduce the number of required calculations. Further, the inclusion of *access roads* and *moving objects* inside them (Layout Objects Typology and Movability) as well as the visibility relationship (Goals and Objectives) would have required a substantially more complicated optimization. Accordingly, they were not included and postponed for future improvement of the model. The approaches taken to build the constructs of this model are summarized in Table 1, where it can also be compared to other models. For example, the representation of the *site space* in this model is similar and comparable to Zouein et al. (2002); or in terms of search approach it can be compared to Easa and Hossain (2008).

9. Concluding remarks

Due to the large number of variables that are involved, the existing site layout models differ significantly in underlying assumptions, and consequently, in their capabilities. The wide range of assumptions and variables in the existing site layout models makes a direct comparison between them difficult. However, a close examination of more than 70 studies published since 1980 revealed that despite their differences, an underlying outline of basic components, referred to as *constructs* in this paper, can be traced among the existing site layout models. Through a parametric, comparative study of the existing models, this study found six common *constructs* that define the common core among these models. It was further noticed that there are also commonalities in the *approaches*, taken or proposed, to address each of the identified *constructs*. The identified constructs along with relevant approaches define a generic outline for site layout planning. This outline can be used for developing new site layout models as well as studying and comparing the existing ones. As was discussed throughout the paper, collectively, the constructs and approaches selected to develop a new model play an important role in the capabilities of the model to accommodate various site layout problems, as well as the quality/limitation of its final outcome. Therefore in developing new site layout models it is important to ensure that the selection of constructs and approaches is a meditated process, rather than a by-product of development process.

Despite the long way that research in site layout planning has come since its early days, there is no report that indicates the use of site layout models in the larger scope in the construction practice. A complete investigation on the reasons behind this can include a multitude of reasons (such as resistance to change) that are beyond the scope of this paper. However, as far as it is related to the context of this paper, lack of flexibility in accommodating the complexity of issues and constraints that are common on construction sites is certainly a contributing factor. Due to the complicated nature of site layout problem and the multitude of factors involved, simplification assumptions were required as a starting point in the research. These simplifications enabled researchers to make fundamental and groundbreaking contributions to the complicated problem of site layout planning in its early days. A glance over the literature that was presented in this paper suggests that as the research on site layout planning has matured over the time, it has moved in the general direction of using more flexible approaches that can accommodate more diverse conditions of construction sites (see Table 1). As an example, while earlier models used a *static* approach to represent the time factor, later models introduced the *phased* approach and more recently, the *dynamic* approach. In addition, the significant advancements of computing technology and the improvements in optimization techniques since the early days of construction site layout modeling in the 1980s, has enabled this general move towards the inclusion of more sophisticated and realistic approaches over the time. A more detailed and realistic approach used to model a construct often entails a more complicated search process in generating a layout. While in the past there could have been a large tradeoff between the complexity of the approach taken to represent a construct and the computational efforts involved, the tradeoff does not seem to be as significant in light of today's advancements of computing technology. For example, the recent 4D dynamic approach developed in Andayesh and Sadeghpour

(2013a), would not have been achievable without the current advancements in the computation technology and availability of new optimization tools. Therefore, the maturity of the research over the time on one hand, and the availability of the advanced computational technology and optimization techniques on the other hand, are making it more possible than ever to develop models that have more flexibility in accommodating and representing the complex nature of actual construction projects with different constraints and conditions. It is hoped that the parametric analysis and comparison of the constructs of site layout models presented in this paper can facilitate a meditated process in the development of future site layout models that offer more flexibility modeling the conditions of actual construction sites.

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