SIMULATION APPLICATIONS IN CONSTRUCTION SITE LAYOUT PLANNING

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ABSTRACT

In the planning phase of every construction project, layout of temporary facilities is a crucial task; site layout can affect safety, travel cost and time, construction productivity, and space utilization. However, site layout planning can be a complicated problem, due to the interdependency of influencing factors. Although interaction among activities is one of the major drivers of site layout planning, it has not been properly addressed in past research. In this study, simulation is presented as a promising tool to address this gap. The capability of simulation technology to model complex processes in construction projects makes use of simulation tools in site layout optimization problems effective, while existing methods are unable to perfectly model these problems, in some cases. Additionally, the advantages and challenges of implementing simulation are assessed and a generic framework for simulation application in site layout planning is proposed.

KEYWORDS

Site layout planning, Simulation, Layout optimization, Construction preplanning

INTRODUCTION

The major aim of site layout planning is to identify required temporary facilities, determine their size and shape, and locate them. Temporary facilities vary in different projects and may include construction equipment, warehouses, maintenance shops, batch plants, residence facilities, fabrication yards, lay-down areas, offices and tool trailers, and parking lots (Tommelein 1992a; Sebt et al. 2008). In practice, it is difficult to determine the savings or loss of money due directly to site layout decisions (Tommelein 1992b). Furthermore, many factors such as construction schedule, mobilization and demobilization of materials, equipment and workers, as well as construction methods influence site layouts (Tommelein 1992b). Consequently, due to tight interactions among these factors, site layout planning becomes so complex that in practice, it is treated "as an isolated problem after many other decisions have been made" (Tommelein 1992b). Figure 1 illustrates the most important factors in layout decisions, as well as the major impacts of a suitable layout on construction projects.

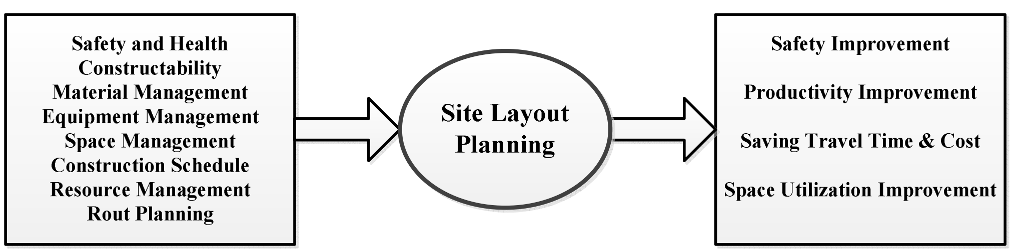

Figure 1 – Decision factors in site layout planning and the impacts of a suitable layout

In this paper, the previous studies on the subject of optimizing construction site layouts are evaluated. Then, the application of simulation in this area is compared with those methods. In the end, a generic framework is presented to demonstrate how simulation is applied in the site layout optimization process.

BACKGROUND

Considerable research has been conducted on many different aspects of site layout planning including how to identify the type and the size of temporary facilities, where to locate facilities, and how to optimize their locations. This study concentrates on determining and optimizing the locations of the facilities. To solve the problem and optimize site layouts, different techniques like Genetic Algorithm (GA) (e.g. Sanad et al. 2008; El-Rayes & Khalafallah 2005; Elbeltagi et al. 2004; Jang 2002), Ant Colony (e.g. Ning et al. 2011; Gharaie et al. 2006), and particle swarm optimization (e.g. Xu & Li 2012; Zhang & Wang 2008) have been employed in past research.

In addition to these optimization methods, some other approaches have been implemented in site layout planning. SightPlan, built based on a knowledge-based system, implemented Artificial Intelligence programming techniques (Tommelein 1992b). An Annealed Neural Network model that is a combination of simulated annealing and Hopfield neural network was presented to lay out predetermined facilities on predetermined locations, while satisfying constraints (Yeh 1995). Easa and Hossain (2008) developed a mathematical model to optimize site layout. Cheng and Connor (1996) developed a system, ArcSite, applying GIS integrated with a database management system that facilitates extracting data from different resources to automatically locate temporary facilities. Since Computer Aided Design (CAD) is a common tool for drawing site layout in practice, some studies have been done to investigate its capabilities in the planning stage of site layout. Sadeghpour et al. (2006) developed a CAD-based model for site layout planning. Various decision support systems have been proposed for site layout planning. To benefit from features of different methods, hybrid systems have also been proposed in this area of research. Zhang et al. (2002) integrated expert System (ES) with Artificial Neural Network (ANN) to compose a Hybrid System for Site Layout (HSSL). This model integrated the advantages of ES, such as a good user interface and consistency with human thinking, and ANN, such as self-adaption and mathematical foundation.

Generally, the main objective in most site layout planning models is to minimize travel time and costs. There are two approaches to define the objective function for optimization: quantitative, where the material handling cost is minimized, and qualitative, where "some measure of closeness rating" is minimized (Rosenblatt 1986). The studies conducted by Jang (2002), Elbeltagi et al. (2004), and Cheng and Connor (1996) are examples of using qualitative methods, and the studies by El-Rayes and Khalafallah (2005), Hakobyan (2008), and Zhang and Wang (2008) are examples of using quantitative methods. Most previous research following either a quantitative or qualitative approach has inspired formulation from the following general term:

$$f = \sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij} d_{ij} \tag{1}$$

Where N is the number of facilities, d_{ij} is the distance between facility i and j, and W_{ij} is the cost per unit length ($/m) for traveling from facility i to j that accounts for the amount and the cost of traveling in quantitative approaches, or W_{ij} is the closeness weight between facility i and j qualitatively determined to account for influencing factors such as safety, traveling costs, trip frequency or other user defined areas in qualitative approaches. In dynamic quantitative methods, the term of relocation costs, which can be considered as fixed or variable costs, will be added to this general term. The variable relocation costs may depend on the type of facilities, and/or relocation distances and places.

It is important to note that it cannot be guaranteed that the site layout resulted from the optimization process of the objective function is the optimum layout when facilities are interacting (Zhou et al. 2009). These methods face several challenges in practice because they only try to find the optimal site layout with the least total traveling costs or the most optimized fitness function which can include safety and environmental issues along with costs. These methods cannot account for many working process factors such as production rate, resource allocation, equipment idleness, and complex relations between activities in construction projects, while simulation tools are able to model the construction process and consider those factors as well as project costs.

WHY USING SIMULATION IN LAYOUT PLANNING?

Simulation is a fast-growing technology in modeling construction projects. Although simulation has been implemented in various sectors of the construction industry like earth moving, tunneling, piping, and steel fabrication shops, simulation capabilities have not been perfectly utilized in site layout planning, and a limited number of simulation applications exist in this area. Zhou et al. (2009) implemented simulation only to evaluate the optimized site layout resulting from GA optimization of the fitness function in tunneling projects. Tawfik and Fernando (2001) used simulation in conjunction with virtual reality (VR) for visualization purposes. In order to plan stock yard layout, a simulation model was presented to analyze three parameters: product handling cost, throughput time for a lorry, and vehicle waiting time (Marasini et al. 2001). In their study, the positions of the storages were predetermined and GA was integrated with the simulation model only to optimize allocation of products to different storage facilities for minimizing throughput time. Consequently, the GA application in this model was only for optimization of product allocation processes, not optimization of the layout. Tommelein (1999) used simulation to find the optimal number of tool rooms and their positions. Although this study showed the promising results of using simulation in construction site layout planning, it implemented simulation for optimizing the layout of only one facility not all facilities. Capabilities of simulation in modeling availability of resources as well as idleness, production rate, and productivity of equipment and labors facilitate the consideration of interaction between activities. To show the advantages of simulation tools and the drawbacks of previously developed methods in site layout planning, we present the following example.

In a construction project, we assume that a temporary facility stores materials that are supposed to be sequentially hauled to Crane1 in the first period of the project time, Part1, and to Crane2 in the second period, Part2. In this problem, the material storage is a temporary facility that must be optimally positioned, and cranes are fixed position facilities. As shown in Figure 2, there are six possible storage positions over an area with 500 meter (m) width and with 100 m intervals. The distance of cranes to the nearest side of this area is 4 kilometers (km). In addition, the same volumes of materials are hauled to both cranes by the same number and type of trucks. Therefore, the cost per unit length for transporting materials is the same in both periods. We solve this problem using quantitative, qualitative, and simulation techniques. In the quantitative and qualitative methods, first, W_{ij} should be determined. For quantitative method, W_{11} and W_{12} represent the cost per unit length ($/m) to transport materials from storage to Crane1 and to Crane2, respectively. As the number and the type of trucks, and the number of material units for both cranes are the same, it is concluded that the cost for transporting the materials from the storage to each crane is the same. Thus, $W_{11} = W_{12}$. For the same reasons, there is no closeness preference between the storage and cranes. Hence, it is decided that the closeness weights of the storage material to the cranes are the same in the qualitative method. As a result, for simplicity, W is used instead of W_{11} and W_{12} in both methods. Therefore, the objective function can be calculated in the quantitative and qualitative approaches, as follows:

$$f = \sum_{i=1}^{N=1} \sum_{j=1}^{N=2} W_{ij} d_{ij} \qquad (2)$$

$$f = Wd_{11} + Wd_{12} = W(d_{11} + d_{12}) \qquad (3)$$

Since, if the storage is placed in any of the six possible positions, the total hauling distance which equals 8500 m (4000 + 500 + 4000) remains constant, the optimization process of the objective function fails. In other words, placing the storage in any of the positions leads to the same result and does not change the value of the objective function. Therefore, any position can be optimal. On the other hand, we simulate the hauling process in the Simphony environment, developed by the Construction Engineering and Management group at the University of Alberta, using the supplementary assumed information shown in Table 1.

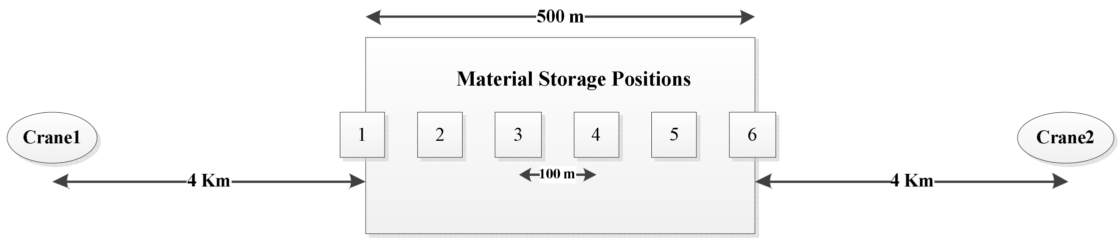

Figure 2 – The configuration of the site

Table 1 – The input data for the simulation model

Description	Value
The number of material units to be hauled to each crane	500
The number of trucks employed for hauling	3
The capacity of trucks (units/cycle)	1
The average speed of loaded trucks (km/hr)	15
The average speed of empty trucks (km/hr)	25
The average loading time (min)	10
The average unloading time (min)	5
The average cycle time of Crane1 (min)	10
The average cycle time of Crane2 (min)	5

Regarding the information presented in Table 1, it is obvious that inputs such as loading and unloading time, the number, speed and capacity of trucks, and the crane cycle time, which cannot be considered in the previous methods as influencing parameters, are required for building the simulation model. Furthermore, it is noteworthy that the only difference between the process of hauling materials to Crane1 and to Crane2 is the crane cycle time, and the other characteristics are the same. The results of the model developed to simulate the construction process with different storage positions are depicted in Figures 3 and 4. As shown in Figure 3, changing the hauling distance does not control the time of Part1, while the time of Part2 is controlled by the distance. This is due to the cycle time of Crane1 being twice as long as that of Crane2. As a result, decreasing the hauling distance for Crane1 only increases the waiting time of trucks queuing for Crane1, as illustrated in Figure 4. On the other hand, reducing the hauling distance toward Crane2 decreases the idle time of Crane2. According to the simulation results, it is concluded that Position 6 is the optimal place for the material storage.

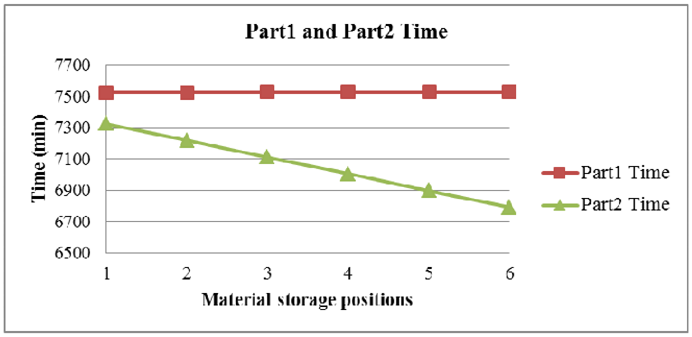

Figure 3 – The results of simulation model in terms of the time of Part1 and Part2

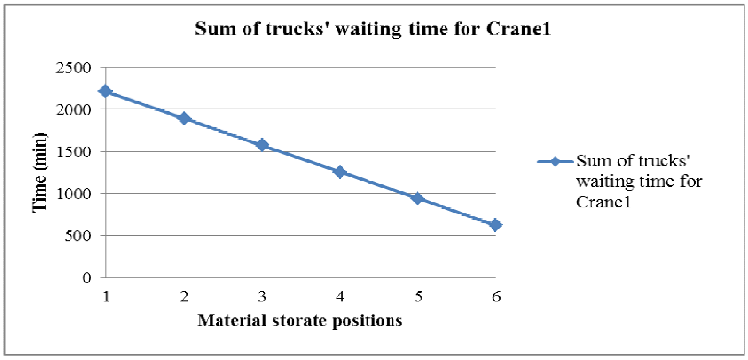

Figure 4 – The results of simulation model in terms of sum of trucks' waiting time for Crane1

This simple example demonstrates how simulation tools can be properly implemented to identify the most suitable site layout, in comparison with the other approaches. In practice, the problems are more complicated. For instance, the size, the number, and the speed of trucks can vary for each crane so that these parameters can highly affect the results. Consequently, in the construction industry, with many interrelated activities and a great number of variables, simulation tools can be more helpful to plan optimum site layouts than the previous methods that consider only work flow costs in the objective function.

SIMULATION ADVANTAGES AND CHALLENGES FOR LAYOUT PLANNING

In comparison with most previous methods, the advantages of using simulation in site layout planning are as follows:

- Due to the many interrelated activities in construction projects, reducing travel distance may not necessarily result in work improvement. Therefore, simulation models can be useful to account for complex interactions among facilities, activities and resources.
- As a result of simulation models, time-based factors such as total project time and resource idleness can be taken into account to assist planners in decision making.
- The input data do not have to be deterministic. Stochastic data can also be implemented in simulation models.

However, there are some challenges for using simulation in this area, as follows:

- The bottleneck of applying simulation in site layout planning is the time and special knowledge required to provide reliable and sufficient input data of simulation models (Koing et al. 2011). While some data are not exclusively defined for logistics such as material quantities, general activities, and milestones, the other data are specifically for logistics and layout planning such as means of transportation and their characteristics (Koing et al. 2011). Hence, some of these exclusive data may not be available in the planning phase of the project.
- While a larger number of influencing factors helps enhance the accuracy of simulation models, it makes the models more complex. Thus, relevant factors must be identified and irrelevant ones should be eliminated (Voigtmann & Bargstadt 2010).
- Determination of the best layout by altering numerous factors and running simulation models many times may not be achieved in a reasonable time window, particularly when stochastic data are used as inputs. Thus, specific knowledge is necessary to identify the most relevant factors (Voigtmann & Bargstadt 2010).
- Since simulation can only evaluate "what-if" scenarios, simulation needs to be integrated with optimization methods, e.g. GA, to automatically search for optimum solutions.
- Simulation is a suitable tool for site layout planning of projects with repetitive activities, close interactions between activities in a tight schedule, and limited number of resources. Otherwise, simulation is not very beneficial.

- Simulation can only evaluate the goodness of the positions of the facilities influencing project productivity and production rate.

PROPOSED FRAMEWORK

To apply simulation in site layout planning of construction projects, we propose a generic framework that can be used in every project with any optimization method, as depicted in Figure 6. Different components of this framework are explained as follows.

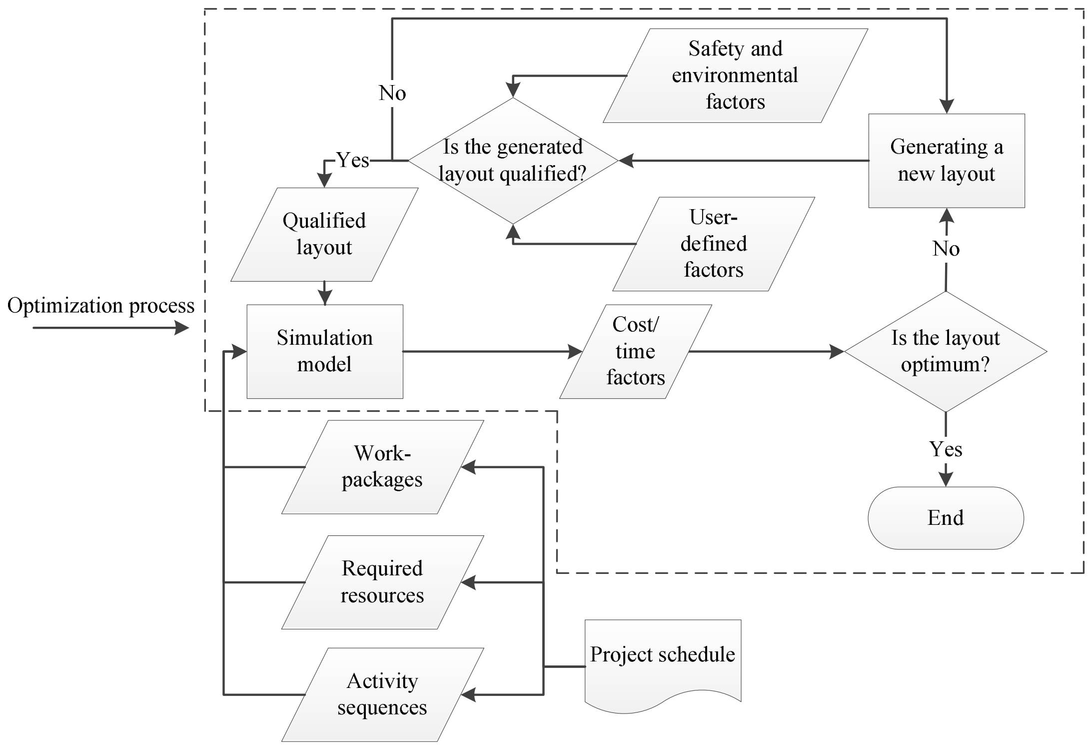

Figure 5: The generic framework for simulation application in site layout planning

Project Schedule

The project schedule is required to build a simulation model. This schedule is similar to the routine schedules prepared for projects, but more comprehensive, because it also consists of all logistic activities. The project schedule includes three components: workpackages, required resources and operation sequences.

Workpackages

Workpackages include main activities and logistic activities. Main activities are defined as activities performed in facilities, e.g. producing concrete in a batch plant. Logistic activities are defined as activities performed between facilities, i.e. personnel, equipment and material flow like transporting concrete from a batch plant to a placement area. The locations of performing activities, activity start date and milestones, and possible delay penalties of late completing workpackages are the attributes of the workpackages. For a main activity, the location is a single facility, while for a logistic activity it is the source and destination facilities.

Required Resources

For each workpackage, the required resources including labor, equipment and material are determined and imported into the simulation model. Quantity of materials, laborers and equipment, crew and equipment production rates, speed of equipment and laborers on site, labor and equipment costs, and productivity factors are the attributes of the resources. Productivity factors affect the production rate in different conditions like inclement weather or congested working areas.

Activity Sequences

The sequences of activities, which are the relationships between workpackages defined in the project schedule, are determined to build the simulation model.

Optimization Process

The optimization process is the main part of the framework. In this process, evaluation of the layout takes place in two stages. First, the feasibility of the layout is evaluated according to safety and environmental factors, and user-defined factors. In this stage, an optimization engine can be employed to provide feasible and qualified layout considering those factors. Then, in the second stage, the qualified layout is evaluated by the simulation model. This approach reduces optimization process time and makes it more efficient because the number of iterations by simulation is reduced. Considering the fact that simulation run time may be long for complex models, evaluation of unfeasible layouts or unqualified layout from other factors' point of view by simulation is not beneficial. In addition, adopting this approach leads to finding the optimum positions of the facilities not influencing the project production rate. The optimization process has the following components.

Safety and Environmental Factors

Safety and environmental issues are the most important concerns in every project. In site layout planning, safety and environmental issues are confined to those that are intensified or lessened by distances between facilities, e.g. the potential hazard of some explosive materials is reduced by increasing the distance away from work areas. In this framework, these factors are taken into account as one of the evaluating factors of site layouts.

User-defined Factors

User-defined factors can be related to hard constraints, e.g. non-overlapping between facilities, soft constraints, e.g. closeness constraints, and user preferences that should be considered in positioning of facilities.

Simulation Model

The built simulation model is integrated with the optimization method and used for determining cost or time factors. The inputs of the simulation model are workpackages, required resources, activity sequences and the feasible site layout, and its output is the cost or time factors.

Cost/Time Factors

Cost factors are limited to resource costs of workpackages, and possible delay penalty costs. Resource costs of logistic activities, i.e. material handling, equipment and personnel flow, directly depend on the distances between facilities. On the other hand, resource costs of main activities and possible delay penalties indirectly depend on the distance between facilities because long distances between facilities can cause late resource availability, which results in delays or idleness of resources for performing main activities. Project time can also be extracted from the simulation model and considered as an alternative to the cost factors for evaluating site layouts is some cases.

CONCLUSION

Site layout planning is a challenging process in the planning stage of every construction project. This problem is not easily solved because of numerous influencing factors and the complexity of construction projects. Most research conducted in this area has tried to simplify the problem by eliminating some factors and considering only traveling distance and costs, as well as some safety issues. However, it is argued that there is always a trade-off between simplifying problems and enhancing the accuracy of models.

In this paper, by solving a simple example with qualitative and quantitative methods, we demonstrated that those methods fail to solve problems in some cases. We also implemented simulation to solve the example, and revealed that simulation could successfully model activity interactions in the project and find the best layout. In addition, we discussed the advantages and challenges of using simulation in site layout planning, and concluded that despite the superiority of simulation over other methods, it requires more data than the other methods for building a model, and lack of accurate data in the planning phase can mainly limit simulation applications. Finally, in order to address how to overcome the challenges, and how to integrate available data resources in the planning phase with simulation models as well as simulation models with optimization processes, we proposed a generic framework. This research is in progress and its outcomes will be presented in forthcoming papers.

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