Dynamic Simulation and Visualization for Site Layout Planning

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Purpose In recent years construction projects have become more complex and time-driven, especially with the rapid rise in the number of active partners involved in each project. Space is regarded as a limited resource on construction sites. Proper planning for site layouts ensuring construction activities can be executed safely and efficiently is until now a time-consuming manual process. Site layout planning relies primarily on the knowledge and expertise of the planner, and is seldom subject to optimization efforts. Often, however, slight modifications to the original site layout plan, can mean limited space resources are allocated more efficiently, costs are reduced, and/or work efficiency is increased. Although construction site layout planning is an important pre-activity, systematic analysis to determine optimal space allocation is difficult because of the complexity of the situation, arising from the large number of engineering resources to be factored-in, and interrelated planning constraints. Space availability on any construction site needs to be considered in relation to scheduling, productivity loss due to path interference, and space constraints. **Method** This a 4D-sitelayout- planning system based on the Monte Carlo method1 is designed to solve space issues in construction sites, and to assist the planner in obtaining the optimal site layout plan. Monte Carlo analysis was executed to iteratively evaluate a deterministic model. This method is often used when a model is complex, nonlinear, or involves a significant number of uncertain parameters. The Monte Carlo simulation presumes that various steps involved in forming a network plan, and estimating the characteristics of the probability distributions for the various site layout plans have been completed. Formulas associated with the generation of normally distributed transportation hours and distances were used. **Results & Discussion** The implementation of this system was carried out in the MicroStation Visual Basic for Applications (MVBA) environment and encapsulates the complicated planning and optimization functions into five easy-to-use modules including management, layout planning, visualization, simulation and analysis. In our system, users can observe simulations of the entire construction process. For each simulation run, the total transportation time and distance of resources is recorded and evaluated, and then a Monte Carlo analysis is performed by the system in order to find an optimal site layout plan. Since space constraints affect the site layout of resources, and influence productivity on the construction site, it is essential that possible site layouts are generated and analyzed in advance, so that the available space can be used more efficiently. Furthermore, efficient construction site planning involves the simultaneous assessment of schedule and site layout so that space can be used more efficiently and dynamically. In response to these needs, this research developed a 4Dsite-layout-planning system to assist planners in developing efficient site layouts, and to monitor the results dynamically and visually.

***Keywords**: layout planning, optimization, Monte Carlo method, 4D visualization*

INTRODUCTION

In recent times, construction projects have become more complex and time driven, especially with the rapid rise in the number of active project participants involved in each project. The construction workspace layout plan not only affects the construction process and its efficiency, productivity, rate of utility of equipment resources, mobility of materials and labor, it is also a major factor that determines construction costs. Therefore, achieving optimal site layouts within the spatial limitations of each construction site has become an important step before the engineering planning stage. Kaming *et al.* (1998) indicated that space conflicts have been identified as one of the major causes of productivity loss in construction[1]. Sanders *et al.* (1989) reported efficiency losses of up to 65% due to congested workspaces and losses up to 58% due to restricted access[2]. Thus it is widely accepted that the site workspace layout exerts a strong influence on construction efficiency. Some researchers have proposed different optimal solutions to solve these workspace and layout planning problems. Although mathematical optimization procedures have been developed to produce optimal solutions, they have only been applicable to small-sized problems. Artificial intelligence techniques have already been applied to solve real-life problems. On the other hand, heuristic methods have been used to produce better but not optimal solutions for large problems. An optimization model has been developed to solve the site layout planning problem, while simultaneously considering safety and environmental issues, and actual distances between facilities[3].

Nowadays, there are many researchers who utilize simulation systems to determine optimal workspace layout plans. In particular, 4D technology, which shows how 3D models will change as the construction progresses over time, has emerged rapidly. This is mainly due to the increasing recognition from the construction industry of the benefits of using the 4D applications, such as increased productivity, improved project coordination, and the optimization of on-site resource allocation. Thus, 4D technology can have a positive impact on both pre-construction and construction phases, because it assists planners in producing improved planned projects by allowing them to see how their plan will evolve[4]. Chau *et al.* (2005) developed a 4D site management model that incorporates the 4D concept into fields of construction resource management and dynamic site planning[5]. Akinci *et al.* (2002) also executed similar research which reduced non-value-adding activities resulting from time-space conflicts. A time-space conflict analysis based on a 4D production model was then proposed[6]. Mallasi's (2004) research developed an innovative computer-based tool dubbed PECASO[7]. This system has potential for assisting site managers in the assignment and identification of workspace conflicts. However, large numbers of building components, workers, equipment and materials share limited space during construction. Since space constraints are likely to affect efficient movement of construction site resources, it is essential to detect and analyze workspace conflicts in advance, such that the available space can be used more efficiently[8]. Normally, the creation of a construction site layout plan relies primarily on the knowledge and expertise of the planner, and is hardly subject to optimization efforts. This paper presents a semi-automatic approach to assist the site layout plan generation process. This research developed a 4D site layout planning system which provides an effective visual environment for the presentation and analysis of space utilization and activity statuses, using techniques such as 3D visualization and 4D simulations with different color codings. The integration of flexible Monte Carlo analysis into a constraint-based simulation concept to determine optimized construction site layout plans is also presented in this paper. Effective site layout plans facilitate efficient resource allocation and result in cost-reduction and increased work efficiency.

RELATED WORK

Construction site layout problems can be described by constraint satisfaction which is a powerful paradigm for modeling complex combinatorial problems. Fig. 1 presents the most frequently-used optimization algorithms for site layout planning.

1. Artificial Intelligence
   - Hegazy and Elbeltagi (1999) proposed a genetic-algorithm-based model for site layout planning[9]. Mawdesley *et al.* (2002) utilized the genetic algorithms in site layout models[10].
   - Yeh (1995) utilized the annealed neural network model to solve the construction-site layout problem[11].
   - Badiru and Arif (1996) proposed a fuzzy linguistic expert system in solving a layout design problem[12].
   - Meller and Bozer (1996) presented an application of simulated annealing to facilitate layout problems with single and multiple floors[13]. Baykasoglu and Gindy (2001) presented a simulated annealing algorithm for the dynamic layout problem[14].
2. Mathematical Model
   - Montreuil (1990) proposed a mathematical programming modeling framework for integrating layout and undirected flow network designs[15].
   - Easa and Hossain (2008) presented a new approach for construction site layout based on mathematical optimization[16].
   - El-Rayes and Said (2009) developed an approximate dynamic programming model capable of searching for and identifying global optimal dynamic site layout plans. The model applies the concepts of approximate dynamic programming to estimate the future effects of layout decisions in early stages on future decisions in later stages[17].
3. Heuristic Algorithm
   - Foulds and Robinson (1978) utilized the deltahedron approach to solve the layout problem[18]. After a planar graph was developed to identify adjacent departments, a heuristic procedure was applied to construct a block layout that satisfied these adjacency relationships[19].
   - COFAD[20] is a modification of CRAFT and includes moving costs for all alternative material handling systems (MHS), thereby integrating the material handling system selection problem with the layout problem.
   - Kaku et al. (1991) used a K-median heuristic to cluster departments into groupings in such a way that inter-group interaction would be minimized where the number of floors determines the number of groups[21].
   - Goetschalckx (1992) developed an efficient method for generating a rectangular block plan that meets area requirements from the dual of a planar graph[22].
4. Simulation
   - Monte Carlo simulations can be applied to tackle the merge-event bias problem[23]. Fan

and Kumar (2010) proposed the use of the Monte Carlo method to simulate the variation of coordinates of the locating contact points[24].

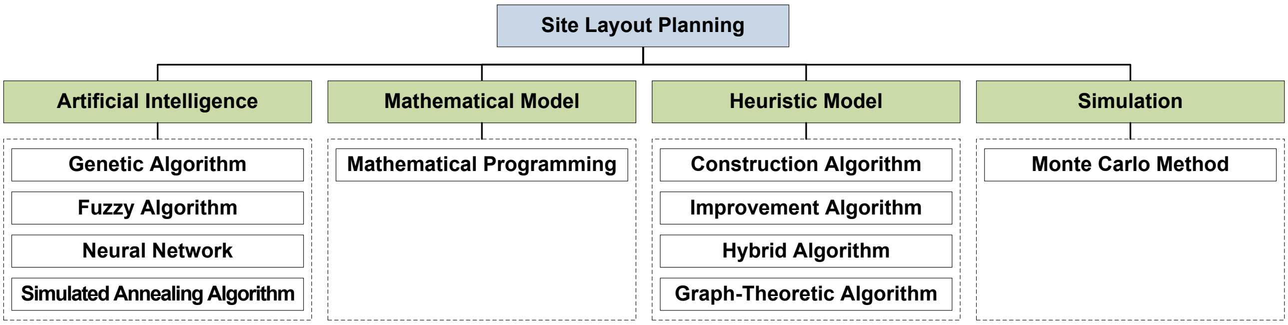


Fig. 1. Frequently used optimization algorithms for site layout planning

METHODOLOGY

Space is a resource that, if not managed carefully, may lead to critical problems arising during construction. This research developed a 4D Site Layout Planning System to assist planners in making efficient use of space resources. Fig. 2 illustrates the overall workflow, which can be divided into four main steps as shown in following sections.

Site Layout Plan Creation

Construction engineers have to properly allocate uses and activities to the various construction spaces, such as Building Areas, Store Areas, Parking Areas, Office Areas and Paths, to minimize the costs of labor and transportation of equipment. Users can plan and create various 3D site layout plans in the 4D Site Layout Planning System.

Constraint-based Simulation

The constraint-based simulation approach was adopted to overcome the limitations of fixed activity graphs and resources availability.

Monte Carlo Analysis

Monte Carlo analysis was executed for iteratively evaluating a deterministic model. This method is often used when a model is complex, nonlinear, or involves more than just a couple of uncertain parameters. The procedures of Monte Carlo Simulation presume that the various steps involved in forming a network plan, and estimating the characteristics of the probability distributions for the various site layout plans have been completed. Formulas associated with the generation of normally distributed transportation hours and distances were used. The concept of movement paths for equipment and workers is shown in Fig. 3, and the related formulas are defined in Eq. (1), Eq. (2) and Eq. (3).

Transportation Distance

The system can calculate the total transportation distance via Eq. (1) and Eq. (2). The distance $d_{i,i+1}$ between Pi and Pi+1 points is given by the formula Eq.(1) : Assume Z=0, in which (X_i , Y_i) is coordinates of P_i and (X_{i+1} , Y_{i+1}) is coordinates of P_{i+1}.

$$\mathbf{d_{i,i+1}} = \sqrt{(\mathbf{X_i} - \mathbf{X_{i+1}})^2 + (\mathbf{Y_i} - \mathbf{Y_{i+1}})^2} \qquad (1)$$

The system will then perform a summation to calculate total transportation distance (D) as shown in Eq. (2), in which N is the number of points.

$$\mathbf{D} = \sum_{i=1}^{N} \mathbf{d_{i,i+1}} \qquad (2)$$

Transportation Time

When the system obtains the total transportation distance (D) of equipment and labor, it can then automatically calculate the transportation time (T) according to their average velocity (V) as shown in Eq. (3).

$$\mathbf{T} = \mathbf{D/V} \qquad (3)$$

Result Analysis

After simulation and evaluation, a near optimal site layout plan will be generated for the impending construction project.

4D Visualization

After generating the near optimal solution, the resulting detailed site layout plan can be easily combined with the 3D model and resources of the project to generate a 4D visualization of the construction process.

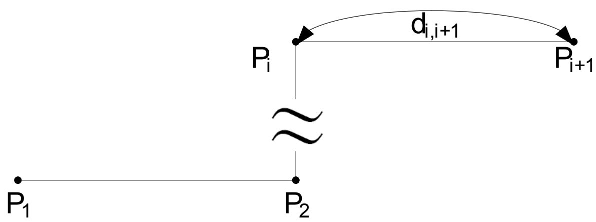


Fig. 3. The concept of moving paths of equipment and labor

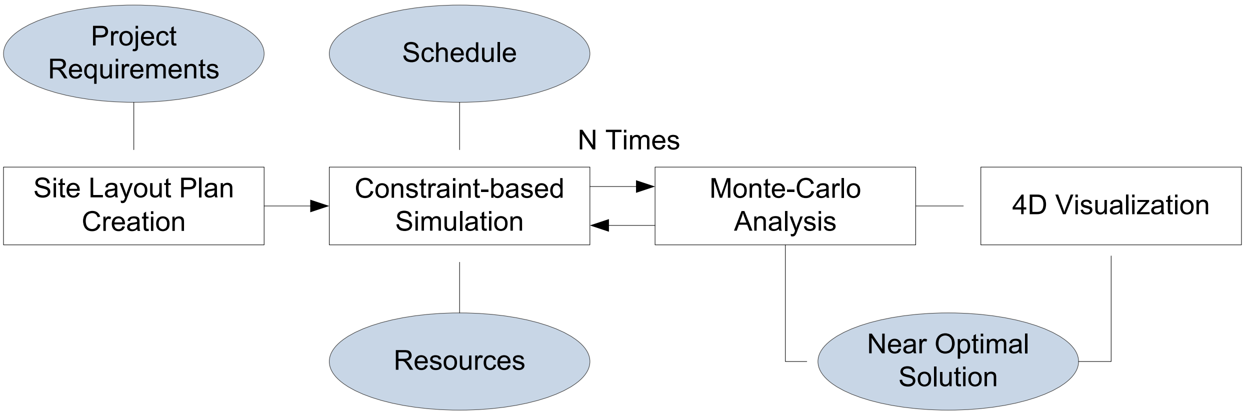


Fig. 2. Workflow of the proposed methodology

SYSTEM DESIGN AND IMPLEMENTATION

As shown in Fig.4, this research takes advantage of Building Information Modeling (BIM) technology to enable the 4D site layout planning system to generate an efficient site layout plan. This system is divided into three tiers: the first tier consists of the BIM models, which describe and store information about entire engineering projects and the results of site layout planning; the second tier is the Bentley MicroStation which provides functions for 2D/3D Data Acquisition, Storage, Editing, Processing, Analysis, Display; the third tier is the 4D site layout planning system developed in this research. The implementation of this system was carried out in the MicroStation Visual Basic for Applications (MVBA) environment, and encapsulates the complicated planning and optimization functions into five easy-to-use modules. These five modules are:

- **Management:** This module is responsible for managing project information and system data, including project schedule and data, resource allocation, 3D models, and site layout planning results.
- **Layout Planning:** This module provides functions for users to create and define the size, location, purpose and exits of workspaces. The layout can be used to simulate and analyze usability and efficiency according to project schedules and resource allocation plans.
- **Visualization:** This system provides tools for defining the relationships between the objects in the 3D model and time schedule. This enables users to understand the processes of construction and resources transportation via 4D visualization. In addition, the system can provide the relevant project information through 1D text, 2D graph and 3D models.
- **Simulation:** In our system, users can observe simulations of the entire construction process. For each simulation run, the total transportation time and distance of resources is recorded and evaluated.
- **Analysis:** The constraint-based simulation is run repeatedly, and then a Monte Carlo analysis is performed by the system in order to find an optimal site layout plan.

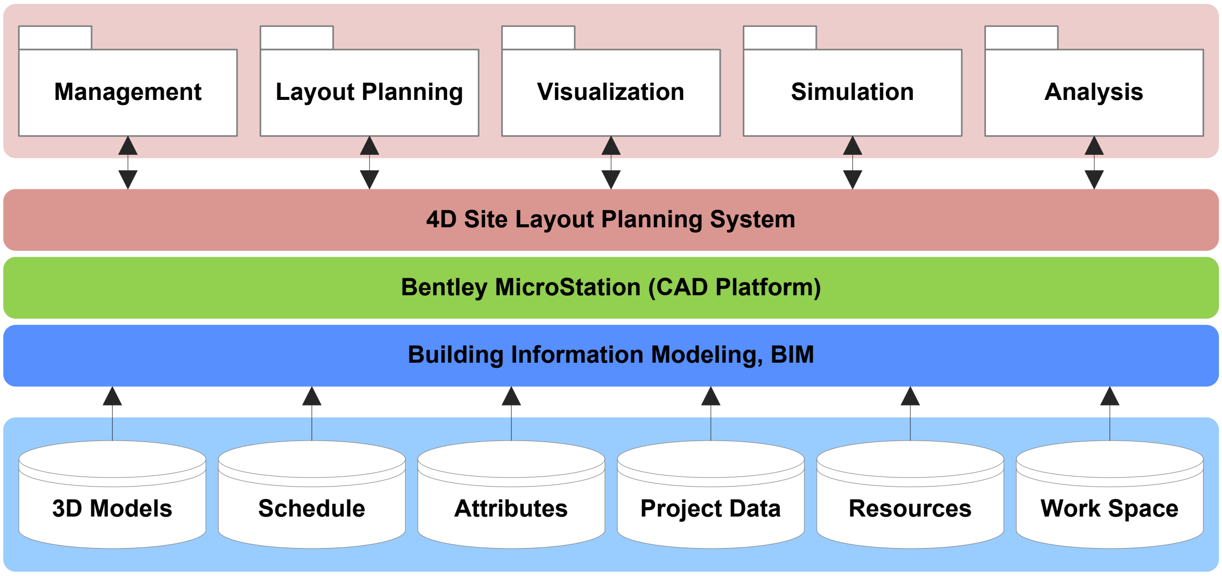


Fig. 4. System framework of the 4D site layout planning system

Demonstration

Example

A simple construction project was used as an example to verify and demonstrate the functionalities of the 4D site layout planning system. The construction project is a 2-floor precast engineering project; the area of the construction site is 80m*42m. In this system, the quantity of the available resources was specified and limited according to the site layout plan.

Table 1 summarizes the simulated variables and constraints in this research. For each resource configuration, a Monte Carlo analysis consisting of many simulation runs was performed, with each run resulting in a different transportation path. From the results of the simulation, planners can select the best solution according to their objectives and their particular needs.

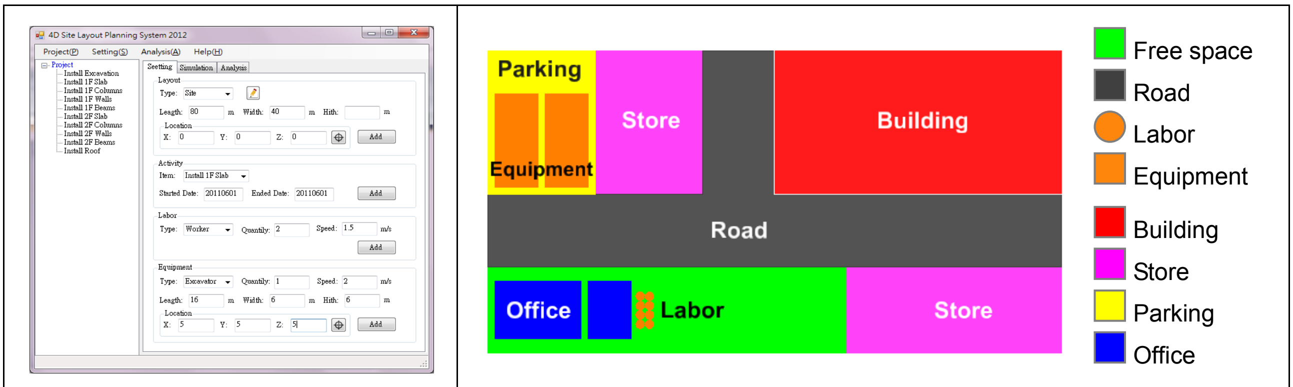
Table 1. Simulated variables and constraints

Site Layout Plan	Labor	Excavator	Truck	Crane
Plan A	12	1	2	3
Plan B	10	1	2	2

Functionalities

The functionalities of this system can be divided into four parts as explained in the following section.

- Fig. 5 illustrates the main graphical user interface (GUI) of the 4D site layout planning system. Before starting the simulation, the user needs to define the resources available for the project. The user can easily manage the activity tree and its resources by creating and adjusting the relationships among the various activities and resources through the GUI, as shown in Fig. 5(a).
- The planner can create various site layout plans in the 3D visual environment for simulation and analysis. The 3D objects in the site model are represented in different colors, depending on their purpose and type. Fig. 5(b) shows the color scheme implemented in this work.
- The constraint-based simulation is then repeatedly run in order to find an efficient site layout. The resultant detailed transportation process can be easily combined with the 3D model of the project to generate 4D visualization as shown in Fig. 6.
- Fig. 7 shows the results of the Monte Carlo analysis conducted in this research. In this example, the shortest transportation time and distance is given by Plan B, as shown in Table 2 and Table 3. The application of Monte Carlo analysis does not guarantee the finding of an optimum solution. However, this approach enables one to analyze and visualize the various candidates of site layout plan, and clearly identify good solutions, albeit manually. Based on transportation times and distances for labor and equipment, one may say that Plan B is more efficient than Plan A.



(a) The GUI for simulation and analysis | (b) The GUI for site layout planning and visualization

Fig. 5. The GUI of 4D Site Layout Planning System

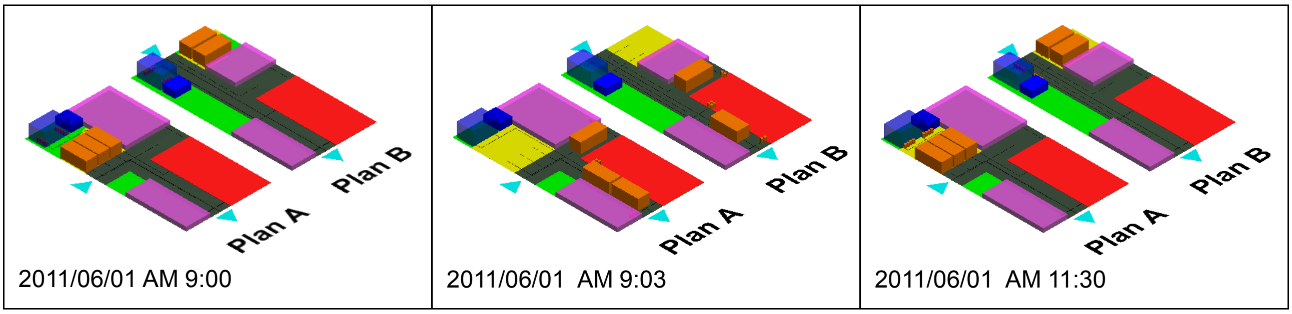


Fig. 6. 4D visualization

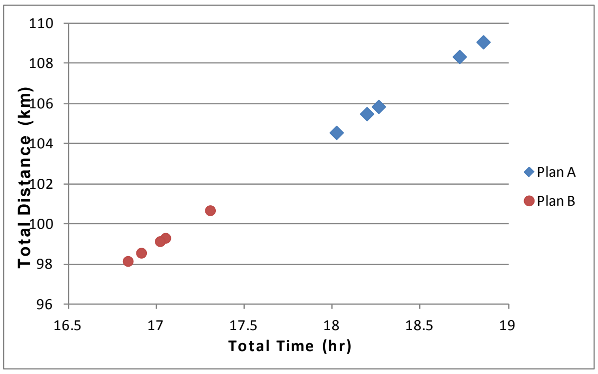


Fig. 7. Results of constraint-based simulation

Table 2 Monte Carlo analysis results of Plan A

Plan A	Min	Mean	Max
Time(hr)	18.02	18.41	18.86
Distance(km)	104.53	106.64	109.04

Table 3. Monte Carlo analysis results of Plan B

Plan B	Min	Mean	Max
Time(hr)	16.84	17.02	17.30
Distance(km)	98.13	99.15	100.57

CONCLUSION

Since space constraints affect the site layout of resources, and influence productivity on the construction site, it is essential that possible site layouts are generated and analyzed in advance, so that the available space can be used more efficiently. Furthermore, efficient construction site planning involves the simultaneous assessment of schedule and site layout so that space can be used more efficiently and dynamically. In response to these needs, this research developed a 4D Site Layout Planning System to assist planners in developing efficient site layouts, and to observe the results dynamically and visually.

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