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A BIM-based automated site layout planning framework for congested construction sites

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ABSTRACT

Site layout planning is often performed on construction sites to find the best arrangement of temporary facilities so that transportation distances of on-site personnel and equipment are minimized. It could be achieved by creating dynamic layout models, which capture the changing requirements of construction sites. However, formulating such models is extremely tedious because it requires much manual data input and changes to design and construction plans are manually updated by layout planners. This study presents an automated framework of creating dynamic site layout models by utilizing information from BIM. The A* algorithm is used in conjunction with genetic algorithms to develop an optimization framework that considers the actual travel paths of on-site personnel and equipment. To address the space limitation on site, our model optimizes the dimensions of facilities and also considers interior storage within buildings under construction. A case example is demonstrated to validate this framework and shows a 13.5% reduction in total travel distance compared with conventional methods.

1. Introduction

Construction site layout planning (CSLP) is a crucial step in construction planning that has been proven to reduce material handling costs while improving safety and productivity of a project [1–3]. Construction projects require a large number of temporary facilities such as material storage areas, fabrication shops, etc. in order to support various construction activities. Traditionally these facilities are set up on unoccupied areas, within the boundaries of the construction site. In such situations the goal of CSLP is to determine the best arrangement of temporary facilities such that the travel distances of construction personnel is minimized [4,5]. An obvious solution could be to set up temporary facilities on the free areas surrounding the building under construction. However, this is possible only on construction sites which have adequate amounts of free area to facilitate such an arrangement. In most urban construction projects, site space is limited and must be used judiciously in order to avoid problems with accessibility, safety and congestion. Comprehensive site layout planning can ensure a smooth flow of materials, equipment, and labour, thereby improving the safety and efficiency of on-site operations.

Site layout models fall into two categories – (1) static layout models, which assume that all of the facilities are assembled at the start and exist for the entire duration of construction [1,4–10], and (2) dynamic layout models, which consider the actual duration for which facilities are required [11–18]. Dynamic layout models are far superior to static models in generating optimum layout plans because they allow layout planners to cater to the changing site requirements and facilitate site space to be reused. Currently dynamic models are created specific to a project, based on the following information – (1) the number and types of facilities required, (2) the dimensions of each facility, and (3) the specific time interval for which each facility would be required on the construction site [19]. In most CSLP tools, such information has to be determined by the layout planner and manually entered into the software program. However manually determining this information could be quite laborious, especially for projects with complex schedules spanning several days. Changes to the design or construction plans would have to be continuously updated into the site layout models, resulting in an inefficient workflow that is very time consuming. This severely limits the practicality of current CSLP tools and is one of the reasons for their failure to achieve widespread adoption by the construction industry. There is a need for a practical and generic tool, which not only reduces unnecessary work by the layout planner but can also be easily adapted for use on different projects. Several research studies have attempted to improve the ease of use of dynamic CSLP tools. Tommelein et al. [2] developed a dynamic layout tool called MovePlan with a graphical user interface, which took activity relationships as input and generated optimized site layouts. Xing et al. [20] developed a GIS- based construction site material layout evaluation tool which took the resource loaded schedule as input to calculate the material accessibility grade on a construction site. Said and El-Rayes [21] developed a construction logistics optimization system, which automated the retrieval of spatial and temporal data from BIM models and construction schedules. In this study, we further improve on the practicality

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of current tools, by presenting a BIM based framework that automates the creation of mathematical models for dynamic CSLP. BIM models are rich sources of information and have been used to facilitate site layout planning [21–26]. The focus of this paper is to leverage information from BIM models and construction schedules, to estimate the size, dimensions and number of temporary facilities required during different stages of construction. Since this methodology is pivoted on BIM, design and construction changes can be automatically integrated into the mathematical models, significantly reducing redundant work by layout planners.

In almost all of the studies on site layout planning, the optimization goal is to determine temporary facility layouts that would minimize on-site transportation costs, without compromising the safety or accessibility of the site. [1–9,11–20,24,27–34]. A common formula used to achieve this is

$$\text{Min}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} d_{ij} f_{ij} \quad (1)$$

where d_{ij} and f_{ij} represent the distance and frequency of trips between two facilities *i and j*, respectively, while *n* represents the total number of facilities. For the sake of simplicity, most early studies on CSLP approximated d_{ij} by using linear distances such as the Euclidean (straight line) or Manhattan (rectangular) distance. However, due to the presence of obstacles it is nearly impossible to always follow straight line paths, due to which the Euclidean and Manhattan distances would be significantly different from the actual travel distances of site personnel. Yahya and Saka [18] introduced the concept of obstruction distance, which was added to the computed Euclidean path in order to approximate the actual travel distances. Park et al. [30] demonstrated the benefits of using actual travel distances instead of linear distances in solving the floor-level material layout problem for an indoor environment. In our study, we use the A* algorithm to accurately compute the actual travel distances between facilities on a construction site, and use them as a basis for site layout optimization. Our method also considers variations in path widths between construction personnel and machines, thereby resulting in a more accurate representation of on-site transportation activities. Another drawback among all of the previous studies on CSLP is that the dimensions of facilities are taken as input parameters, prior to performing the optimization. As a result, only the position and orientation of each facility are considered as the decision variables for optimization. As will be demonstrated in this paper, the previous approach severely limits the range of possible solutions. In this study, we consider the position, orientation and dimensions of each facility as decision variables, which are then optimized using Genetic Algorithms (GA). As a result, our CSLP tool determines the optimal dimensions of each facility, significantly improving the efficiency of generated layouts. To facilitate the use of GA, a modified crossover and mutation operator has been developed in this study.

A characteristic of urban construction projects is the lack of on-site storage space. To make up for this shortage of space, layout planners may assign storage facilities to be set up inside the buildings under construction [31]. Such an approach increases the total area for setting up of facilities and consequently reduces on-site congestion. However, the interior regions of a building are active workspaces for a number of floor-level construction activities [35]. This imposes a limitation on the amount of space that can be used for interior storage. As a result, interior storage plans must be planned and coordinated carefully, to ensure maximum utilization of the available space. Park et al. [30] developed a system framework to optimize the interior storage locations of construction materials on every floor of the building under construction. However, their study was limited to optimizing storage locations in interior spaces only and did not address the storage needs in exterior regions of the construction site. Elbeltagi et al. [13] developed a dynamic CSLP tool, which used the constructed space of a building to store temporary facilities, with a view to reduce congestion. Said and El-Rayes [15] proposed a congested construction logistics planning (C2LP) model that generates optimal material logistics and site layout plans. The C2LP model requires input parameters such as the site exterior and interior spatial data, dimensions of temporary facilities, their relationship with activities on the construction schedule and material assignment to activities, based on which it optimizes the storage locations in exterior and interior building spaces. In a following study, Said and El-Rayes [21] developed an automated multi-objective construction logistics optimization system (AMCLOS), which uses information in BIM models and schedules to optimize the utilization of interior storage spaces in a building. The AMCLOS system uses IFC (Industry Foundation Classes) files to extract the geometry of interior and exterior site regions, thereby automating the computation of available storage space. However, the permissible periods of interior storage areas of the materials and dimensions of each temporary facility have to be manually specified in the AMCLOS system. In our study, we leverage information from BIM models to develop an automated method for interior and exterior storage optimization. At any particular instant of time, the amount of interior storage space is dependent upon the number of completed floors, the geometry of the building and the presence of floor-level construction activities. By linking material and spatial data from BIM models to activity data from the schedule, we are able to automate the computation of available interior storage space during different stages of the project. Our framework also automates the computation of required storage amounts for each material, and optimally assigns them to different storage locations. Therefore, this study presents an automated framework for CSLP, which addresses the requirements of congested construction sites by utilizing interior building spaces to store materials. Our framework, which relies on BIM, enables us to develop a CSLP model that is generic enough to be useful in a variety of cases. The number of inputs from layout planners is minimized since most of the computations are performed on information available from the BIM model and construction schedule.

Our framework for automated CSLP using BIM consists of three modules (see Fig. 1). In the first module, BIM based facility size estimation is used to accurately compute the required size and dimensions for each facility. In the second module, we present a methodology framework to automate the creation of dynamic layout models. The third module deals with formulating the objective function and using an actual travel path driven optimization to generate facility layouts. A demonstrative example is considered to highlight the benefits of this new approach.

2. BIM-based facility size estimation

The CSLP problem consists of optimizing the locations for temporary facilities, which may be approximated as one or more rectangles, on the unoccupied areas of a construction site. Most CSLP tools require the user to specify what the dimensions of each facility are, prior to performing the layout optimization. However, this approach has a significant drawback, which leads to an under-utilization of site space. Facilities are used for storing materials and equipment, or to provide a working area for humans. It is thus essential that the facilities be large enough to satisfy these requirements. For example, it could be specified by the layout planner, that a site office with 10 engineers should provide a floor area of 100 m^2. However, its exact dimensions can only be decided after taking into consideration the dimensions of the available space which it is to be set up on. The facility in this case can take the form of a variety of rectangles with different values of length and width. The only constraints imposed are that the facility should provide the necessary floor area while being of reasonable dimensions. Hence, specifying a fixed dimension for a facility prior to assigning its location on the site severely restricts the range of possible solutions. On construction sites with limited spaces, it is thus essential to optimize the dimensions of each facility according to the dimensions of the available site locations. In this study, we consider their dimensions as variables, which are optimized using Genetic Algorithms.