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A BIM-based approach for automated tower crane layout planning

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ABSTRACT

Tower crane layout design and planning within construction site is a common construction technical issue, and is regarded as a complex combinatorial problem. Previous research focused on utilising either mathematical methods or visualisation tools to find an optimal tower crane layout plan. Both these two approaches require large amounts of manual data input by the layout planners, which is time-consuming and not very practical in industry. The purpose of this paper is to develop an integrated approach which combines Building Information Modelling (BIM) and Firefly Algorithm (FA) to automatically generate an optimal tower crane layout plan. Firstly, BIM is utilised to provide inputs for the mathematical model. Then the FA is used to determine the optimal locations of tower cranes and supply points. Finally, the optimal tower crane layout scheme will be visualised and evaluated through BIM-based simulation. A practical case is selected to demonstrate the proposed approach. The final result is promising and demonstrates the practical value of this approach.

1. Introduction

Effective tower crane layout design and placement within a construction site is a common construction technical issue, and is regarded as a complex combinatorial problem. To transport heavy materials, such as rebar, formwork, scaffolding, equipment and steel component, tower cranes are needed and should be well located to reduce construction cost and safety hazards [1–5]. Tower crane layout planning is a multi-objective problem, and is affected by many uncertainties and variations. To facilitate the decision-making process, many static and dynamic mathematical approaches had been developed [1–7]. However, modelling the dynamic facility requirements of a construction site is a complicated task, and takes a significant amount of time and effort by the layout planner [8]. In addition, most of the current tower crane layout systems require a large number of project specific variables to be inputted and updated manually which is time-consuming [2,8,9].

To tackle these issues, this paper proposed an automated tower crane layout planning system by leveraging Building Information Modelling (BIM) technology. BIM is emerging as a method of creating, sharing, exchanging and managing the information throughout life cycle between all stakeholders [10–16]. There are various types of information stored in BIM model including 3-Dimension (3D) spatial data, 4-D schedule data, 5-D cost data, 6-D facility data and n-D data. These data are more coordinated, more reliable, of better quality, and more internally consistent than traditional Computer Aided Design (CAD) data [15]. In addition, any changes within BIM will automatically trigger the adjustment of all the related elements and information so as to provide stringent quality assurance [15].

According to Fister et al. [17], Firefly Algorithm (FA) is simple, flexible and versatile, which is very efficient in solving a wide range of diverse real-world problems. Nowadays, FA has been applied for solving many optimisation problems in practice including combinatorial optimisation, constraint optimisation, dynamic and noisy optimisation, continuous optimisation, and multi-objective optimisation [17].With regard to efficiency and effectiveness, FA is selected to calculate the optimal locations of tower cranes and supply points by analysing construction requirements and site conditions.

The synergy of BIM and FA opens up new possibilities in the field of tower crane layout planning. BIM can not only be used to provide automated inputs for FA but visualise and validate the abstract outputs from FA. The structure of this paper is as follows: Section 2 reviews the recent studies related to tower crane layout planning from two perspectives: mathematical optimisation and 3D tools-enabled virtual simulation. Section 3 describes a framework of BIM-based automated tower crane layout planning system. Three modules, including the BIM platform, the mathematical model, and the visualisation and operation simulation model, within the framework are mentioned and explained in details. Section 4 provides a case study to demonstrate and evaluate the proposed framework in Section 3. Section 5 concludes with the summary of contributions including both theoretical and practical contributions.

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2. Related research studies

A significant number of studies have been implemented in tower crane layout optimisation and operation simulation so as to reduce total operation cost. These research studies can be classified into the following two main categories:

2.1. Mathematical model driven optimisation for tower crane layout

Tower crane layout optimisation attempts to find the optimum locations of tower cranes out of the available alternatives in order to satisfy criteria. These criteria can include: balancing the workload and reducing the total crane operation time, or minimising the spatial conflicts between tower cranes and other moving resources on the site [18]. In 1983, Rodriguez-Ramos and Francis [19] developed a mathematical prescriptive model to establish the optimal location of a single tower crane within a construction site. Later, a stochastic simulation model was proposed by Zhang et al., and they showed that 20–40% of hook horizontal travelling time could be saved by using this model [20]. In large projects, when a single tower crane could not satisfy the construction requirement, more than one was employed to undertake transportation tasks. In order to optimise locations for a group of tower cranes, Zhang et al. [5] subsequently developed another computerised model to balance the workload, minimise the likelihood of conflicts with each other, and improve the efficiency of operation. However, these models above just singled out the tower cranes with the predetermined geometric layout of all supply and demand points, together with the type and number of tower cranes. They neglected the interrelated effect between locations of the tower crane and supply points and the space competition among various supply points [7]. Genetic algorithms were utilised to address these problems and optimise the site layout [7, 21–23]. For example, Tam et al. [7] had investigated and analysed the relationship between the key supply areas and the tower cranes, and developed a genetic algorithm model to optimise the above facilities, taking into account the complexity of the relationship between these facilities. In addition, annealed neural network [24] and hybrid incremental solution method [25] were also utilised to optimise construction site layout.

In recent years, some emerging algorithms and enhanced mathematical models have been developed to solve the tower crane layout optimisation problem, such as artificial neural networks [4], entropy technique [21], ant colony algorithm [26], particle swarm algorithm [27], and hybrid swarm intelligence [28]. To enhance the general practice of dynamic construction site layout planning, Xu and Li [29] proposed a fuzzy random multi-objective decision making model. Yahya and Saka [30] utilised multi-objective artificial bee colony algorithm with levy flight to optimise site layout planning. Some enhanced mathematical models were also proposed to simulate the real practice. El-Rayes and Khalafallah [31], Sanad et al. [32] developed an expanded site layout planning model which was capable of maximising construction safety and minimising the travel cost of resources on site, simultaneously.

In summary, many research studies that address the problem of optimising the location and transportation time of tower cranes have been published and most of them have proved their application value. However, the manual input process is time-consuming and severely restricts the utilisation of these models in practice. In addition, the outputs of these mathematical models are abstract and are often hard to fully understand by site planners.

2.2. Technology-enhanced tower crane layout planning and operation simulation.

Due to the complexity and the large number of factors involved, visualisation and virtual simulation proved to be an effective tool for decision-makers to fully understand complex construction site layout planning [22,33–35]. Geographic Information System (GIS) was applied to analyse the objects which already existed on construction site [2,36]. Cheng and O'Connor [37,38] had used GIS for site layout of construction temporary facilities. Irizarry and Karan [2] tried to integrated BIM and GIS for optimising locations of tower cranes. Su et al. [36] developed a GIS-based dynamic construction site material layout evaluation for building renovation projects. CAD had been experiencing great advances since the late 1980s. Koo and Fischer [39] conducted a feasibility study of 4D CAD in commercial construction and found that 4D models were effective in evaluating the executability of a construction planning. Sadeghpour et al. [40] and Osman et al. [22] both presented a CAD-based site layout model designed to account for the diverse nature of construction sites. Some other visualisation tools such as 3D MAX were also utilised to improve tower crane operation efficiency [33,34].

Detailed crane motion planning was also investigated to help the crane operator navigate the crane motions safely and efficiently [18, 35,41–45]. Kang et al. [46] had developed a system for providing detailed planning and visualisation in a virtual construction environment as well as for assisting crane operators in real-time during erection. Shapira et al. [44] developed a vision system for tower crane to eliminate blind lifts. Lee et al. [47] introduced a newly developed tower crane navigation system that provided 3D information about the building and surroundings and the position of the lifted object in real time using various sensors. Several collision–prevention approaches were also proposed by [35,41,42,45], which comprised of real-time data collection platform, a visualisation module, and a decision module, to real-time monitor equipment operations and assess the possibility of collision. In addition, Li and Liu embedded an experience-based and practical alarming system into the virtual monitoring system [35].

BIM is an emerging technology in construction industry and had been implemented in different stages in the last few years [14,16, 34]. When comparing with GIS, CAD, 3D MAX and other visualisation tools, BIM contains more physical and functional characteristics of a facility. BIM is also a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle [15]. However, few studies had been conducted to utilise BIM to improve construction site layout planning or tower crane operation planning [8,9]. This paper will investigate the integration of BIM and mathematical optimisation method for automated tower crane layout planning.

3. BIM-based automated tower crane layout planning system

This section describes a framework of BIM-based automated tower crane layout planning system (as shown in Fig. 1). There are three modules in the framework: module A, B and C, standing for BIM platform, mathematical model for tower crane layout planning, and BIM-based tower crane layout visualisation and operation simulation, respectively. Module A provides inputs for module B to automatically generate alternatives of tower crane layout. Each alternative will be visualised and evaluated through module C. The output of module C will be the final implementation scheme.

The proposed system integrates the highly intelligent BIM platform with the novel mathematical method for producing the desired tower crane layout. The main advantage of the system is the utilisation of BIM data as mathematical model input so as to reduce manual input. The fact that most projects have already use BIM for design and construction greatly facilitates the feasibility of the system. Intelligent algorithm is then employed to perform the calculation and optimisation process. Following the mathematical step, the system can further visualise and simulate the alternative tower crane layout plans based on BIM platform. Different project participants can be involved to discuss and evaluate the alternatives, and also give significant suggestions based on their work experience so as to make the final tower crane layout scheme more practical and useful.