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Automated tower crane planning: leveraging 4-dimensional BIM and rule-based checking

Yuanshen Ji*, Fernanda Leite

Construction Engineering and Project Management Program, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 301 E. Dean Keeton St. C1752, Austin, TX 78712-1094, USA

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ABSTRACT

Reviewing tower crane plans in the pre-construction phase is an iterative process and one that is in need of an approach that improves its effectiveness and efficiency. This study proposes a framework that integrates 4D modeling and rule-based checking for reviewing tower crane plans. A template of crane-specific rules that are based on prevailing tower crane design standards in the United States was developed. This framework is capable of automating the review process and identifying potential spatial and capacity conflicts based on design models and construction schedules. This work presents a prototype system to which crane-specific rules are applied in a rule-checking platform that uses a 4D model as input. In the validation tests, the system's effectiveness is demonstrated by its high recall rates. Efficiency is achieved through diminishing manual interventions. The proposed approach also gives rise to an automated tower crane-planning process, reducing the need for manual input. Higher efficiency allows users to review more alternatives consistently when compared with the manual approach.

1. Introduction

The last decade has seen a broader adoption of tower cranes on building construction projects in North America as well as around the world. The presence of tower cranes is especially prevalent in high-rise building construction and in projects with high levels of prefabrication, which rely heavily on machinery equipment for material handling activities [1,2]. The benefits of tower cranes over mobile cranes include higher productivity rates [3] with reduced safety-related risks [4–6] and decreased daily operations management demands [7,8].

To leverage such benefits, project engineers need to invest time in the preconstruction phase by planning the placement of the possible tower cranes in their specific jobsites [1]. This extra planning effort is needed because of the complex interactions between the design and the other parts of site layout—interactions that have cost, safety, and productivity implications [9–14]. Moreover, extra planning is needed because of the timing of the design, which occurs long before execution [15]. Planners need to synthesize project data and generate hypothetical scenarios in which engineers can review proposed design alternatives. The hypothetical scenarios reflect designers' personal understanding of site-specific conditions (e.g., spatial, time-space, or availability constraints) based on their engineering experience. Therefore, an enhanced design process should aim to eliminate the risk of overlooking critical conditions (i.e., hypothetical scenarios in preconstruction planning) that might make certain tower crane plan alternatives unfeasible; such a process could also facilitate the disclosing of constraints that are unique to each project.

The effectiveness of advanced tower crane planning systems is affected by various factors. Tangible factors include the geometric relationship between the crane and site [12,16] along with permissible equipment specifications [9,17]. Intangible factors include the number of repetitive and manual tasks that, in actual projects, implementing these systems can give rise to. Users can be quickly overwhelmed by excessive manual iterations, directly impacting the performance of advanced design systems.

The solution space for tower crane planning problem is multi-dimensional. Each solution belongs to a three-dimensional space, which features critical conditions, site-specific constraints, and design alternatives, as shown in Fig. 1. Each cell in the solution space cube has a value with respect to each dimension. Those getting the "passing" values from all attributes of critical conditions and site-specific constraints are feasible solutions. The feasible solutions are difficult to identify because each dimension of the tower crane solution space has multiple attributes. For example, critical conditions may include but are not limited to critical lift, erection, dismantle, height alteration, and maintenance. Finding the cells with a "passing" value from each

* Corresponding author.
E-mail addresses: yuanshen@utexas.edu (Y. Ji), fernanda.leite@utexas.edu (F. Leite).

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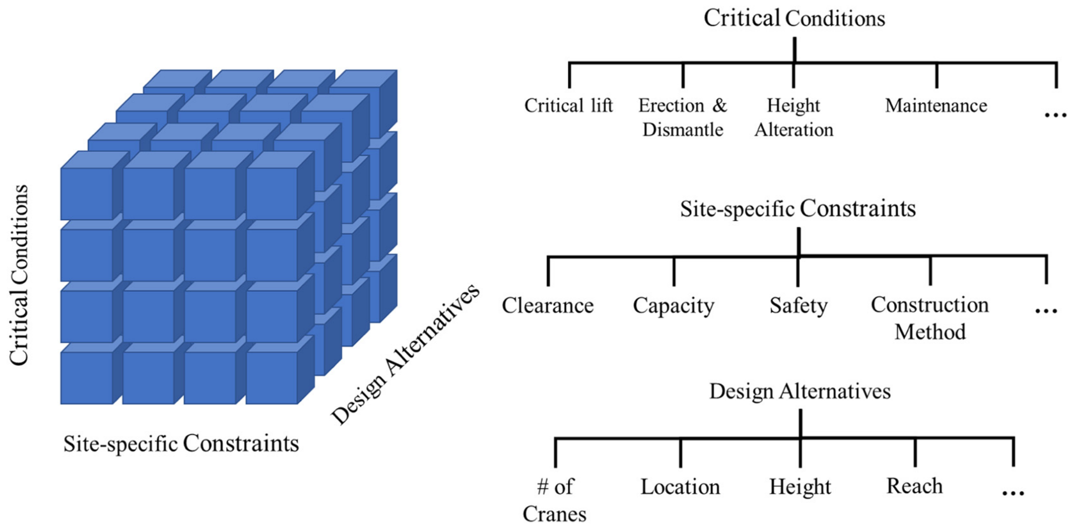

Fig. 1. Example solution space of tower crane design in building construction projects.

attribute of every dimension is an iterative, time-consuming, and often manual process. Manual iterations can be reduced, if not eliminated, by an approach for enhanced tower crane planning.

The ultimate aim of this research study is to improve the effectiveness and efficiency of tower crane planning. We propose an enhanced design system for tower crane planning to eliminate repetitive tasks and manual information input. The proposed framework defines effectiveness as a system that permits engineers to expand the search space (see Fig. 1) within a limited time frame and explore more options for an optimum solution; efficiency refers to reducing the number of repetitive tasks. To improve a building information model (BIM)-based planning system, we leverage 4D modeling and rule-based checking. The following section summarizes the milestone research studies in the field that have utilized 4D and rule-based design to enhanced project outcomes, including improved productivity for construction planning and management. The remainder of this paper introduces the proposed approach, provides a demonstration of our prototype implemented on an actual construction project, and presents a discussion of the results, including listing limitations for further exploration.

2. Background research

A considerable amount of effort has been invested in developing design systems to support crane planning. These systems [18–23] enable users to understand the alternative's impacts on project success. Many advanced systems, however, are typically devised for reviewing selected challenging scenarios for higher accuracy and automation rather than for tackling the large amount of general, iterative checking requirements. To bridge the gap between the status-quo and a broad adoption in actual projects, designers must come up with a system that improves usability, reduces manual data input and iterations, and automates the repetitive activities along the process. Nevertheless, pioneering studies have identified key characteristics that have the potential to reduce manual as well as iterative activities. The major findings in this regard are summarized in this section. Indeed, these research studies serve as points of departure for this study.

2.1. Simulation and 3D visualization for lift planning

Simulations cannot replace human intervention when it comes to space or time-space conflicts [24,25]. In the late 1990s, Stanford University researchers at the Center for Integrated Facility Engineering (CIFE) introduced to the architecture, engineering, and construction (AEC) community the concept of 4D simulation, originally termed "4D-CAD" [26]. This approach integrates 3D models and project schedules to generate a 4D simulation. A 4D simulation, compared to synthesizing a process hypothetically, is a much more intuitive, efficient, and effective way to understand the construction process. This concept was quickly embraced by the AEC industry and many applications have since been developed and implemented.

Al-Hussein et al. [9] conducted a study that explored an approach to complement simulation with visualization. It reduces difficulties stemming from lack of proficiency in generating detailed simulations, a skill that engineers are not typically trained for. They claimed that the integration of a 3D model and lifting event simulations is helpful in validating lifting plans. However, users of this system have to rely on visuals to identify the conflicts associated with each simulated event. The system cannot proactively capture spatial conflicts or capacity limitations that invalidate the simulated event. Several research studies [16,21] experimented with model-based simulation for lift planning. Shorter operation time can be achieved. However, these proposed approaches may generate plans without identifying spatial conflicts that commonly exist during implementation. Furthermore, these approaches are not capable of assisting in pre-construction planning. The amount of effort required to generate one single simulation in these studies is costly for implementation in pre-construction planning, which typically requires validating hundreds of events and scenarios.

2.2. Kinetic motion of cranes

The reach and range of motion of crane components are dynamically affected by the load applied on the hook. Tower crane planning needs to iteratively check these factors for validation. Tantisevi and Akinci [15] developed a system to automatically generate sequential movements of mobile cranes to support the detection of spatial conflicts and a boom's range of motion. The system can restrict the allowed range of motion dynamically according to payload under the hook. However, this system still requires a significant amount of manual data input to develop the initial crane model. More importantly, the framework does not support validating the clearance that is critical for crane safety.

Kang and Miranda [27] explored lift path planning using the kinetic motion of cranes as constraints. The outcome of the path-planning algorithm can avoid physical collisions for individual lift activities. Hence, this approach is especially useful in crane collaboration planning and critical lift planning. It is challenging to apply this approach in pre-construction planning, which has a large solution space and does not only plan for a single event.