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Automatic design and planning of scaffolding systems using building information modeling

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ABSTRACT

Considering their significant impact on construction projects, scaffolding as part of the temporary facilities category in construction must be thoroughly designed, planned, procured, and managed. The current practices in planning and managing scaffolding though is often manual and reactive, especially when a construction project is already underway. Widespread results are code compliance problems, inefficiency, and waste of procuring and managing material for scaffolding systems. We developed a rule-based system that automatically plans scaffolding systems for pro-active management in Building Information Modeling (BIM). The scope of the presented work is limited to traditional pipe and board scaffolding systems. A rule was prepared based on the current practice of planning and installing scaffolding systems. Our computational algorithms automatically recognize geometric and non-geometric conditions in building models and produce a scaffolding system design which a practitioner can use in the field. We implemented our automated scaffolding system for a commercially-available BIM software and tested it in a case study project. The system thoroughly identified the locations in need of scaffolding and generated the corresponding scaffolding design in BIM. Further results show, the proposed approach successfully generated a scaffolding system-loaded BIM model that can be utilized in communication, billing of materials, scheduling simulation, and as a benchmark for accurate field installation and performance measurement.

1. Introduction

Temporary facilities such as scaffolding systems, formwork, and shoring systems are structures that assist mainly in the placement of bulk materials. Most construction projects utilize temporary facilities frequently, and construction safety, quality, speed, and profitability are impacted by using temporary facilities [1]. Some aspects of these are elaborated further.

Temporary facilities can cause spatial and temporal conflicts between other temporary facilities or activities which can then lead to unsafe conditions and loss of productivity [2]. According to Ratay [3], many construction disasters occur due to the failures of temporary facilities during construction. In addition, the Construction Industry Institute (CII) highlighted in a recent research study that temporary facilities form one of the top four primary cost categories belonging to indirect construction costs [4]. In the author's opinion, temporary facilities, to which scaffolding systems belong, deserve much more attention due to the impact they have on labor cost and construction schedule.

Scaffolding systems have significant impact on successful project delivery. The same research report by CII interviewed 56 owner and contractor companies. Results show that these companies consider scaffolding systems, and its construction and deconstruction, as one of the most challenging and wasteful component among the 16 subcategories of indirect construction cost [4]. In addition, other concerns were identified which matter for project success. The Occupational Safety and Health Administration (OSHA) [5] and Workplace Health and Safety Queensland (WHSQ) [6,7], for example, reported that there exist repeated code-compliance problems related to scaffolding systems. OSHA reported also that 65% of the construction workers are frequently on scaffolding systems. It further states that preventing accidents associated with scaffolding systems exclusively can protect workers from about 4500 injuries and 50 deaths annually and save American employers spending $90 million on lost workdays [8]. Since work site productivity and safety go hand-in-hand, these statistics justify additional efforts towards optimizing design, planning, and utilization of scaffolding systems.

Despite the aforementioned issues and the importance of temporary facilities to a construction project, there are currently several problems in planning and managing these in the construction industry. First, most temporary facilities (incl. scaffolding systems) currently lack effective front-end planning and

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management. Architectural and bid drawings typically do not incorporate temporary facilities except for exceptionally complex temporary facilities such as cofferdams [9,10]. Although some construction plans include important temporary facilities late in the construction planning process, they are often installed at construction sites when needed but without sufficient planning effort. Furthermore, due to the lack of time and understanding, calculations and drawings of scaffolding systems submitted by temporary facility vendors are most often reviewed only to assess their impact on the permanent part of the building [9].

Along with the lack of front-end planning and management, current industry practices suffer from heavy reliance on the knowledge and experiences of individual engineers. Even though software programs exist that are specialized in designing temporary facilities (e.g., formwork and scaffolding), the functions of these commercially-available software programs are often limited to rapid generation of temporary facility designs. Only human cognition, based on visual analysis of the building designs or the construction sites, provides the basis for detecting locations where temporary facilities are required. It is today's human decision makers that determine the proper types of temporary facilities and they typically generate the corresponding detailed designs.

Due to the complex nature of construction projects and potentially imperfect human judgment, there are opportunities to reduce or eliminate potentially erroneous temporary facility planning; especially in projects which are planned manually based on visual analysis of the construction site drawings and schedules. Some examples of errors are: necessary temporary facilities can be omitted in a construction plan; improper types of temporary facilities can be selected; temporary facilities design may not reflect the design requirements; and, accordingly, the amount of materials and associated cost for temporary facilities cannot be estimated accurately.

Taking into account the impact on the entire construction project and the deficiencies of the current practices in planning and managing temporary facilities, the industry needs to overcome these drawbacks by enabling thorough front-end planning of temporary facilities – and in this case – scaffolding systems.

This research addresses the articulated problems by integrating scaffolding systems into BIM-based construction planning. While a growing number of construction projects utilize BIM technology and processes already in order to incorporate temporary facilities into the construction plans, most of such planning is done manually. Taking advantage of the rich information available in BIM models, we attempt to automate most of the processes of: assessing the construction site condition that changes according to the construction schedule, detecting required scaffolding systems and generating the design, visualizing them in the building model and construction simulation, and generating periodical utilization schedules and reports.

In order to automate these processes, our research developed an automatic rule checking system for temporary facility planning focusing on traditional pipe and board scaffolding systems. Deciding where scaffolding systems are required and how they can be built satisfying various design and safety requirements are part of the research questions. Automated type or vendor selection of the scaffolding systems was not part of scope of the work. The research first established an initial rule related to scaffolding system installation. Then, the developed rule checking system was used to check the model at an early construction planning stage. The presented results are in the form of building models and construction simulations loaded with scaffolding systems and automatically generated reports.

This paper is organized as follows. The background section reviews the current industry practices and technology in support of scaffolding system planning and discusses the need for an automated solution. The section thereafter presents the proposed framework and methodology of the rule-based system for scaffolding system design, planning, and management. The customization of the automated system for scaffolding systems is presented in the following section. The final section shows the implementation of the scaffolding planning system for a realistic building model. The results from the case studies validate the feasibility of the proposed system by creating a realistic construction plan containing scaffolding system. The final section discusses limitations and contributions of this research, and potential future research.

2. Background

2.1. Current industry practice in temporary facility planning and management

The production plans of construction projects differ from the production plans in other industries such as manufacturing. In addition to the complex and dynamic nature of construction projects, the need for potentially extensive temporary facilities distinguishes construction plans from manufacturing plans. Manufacturing plans for mechanical components describe what manufacturing tools, e.g. drills and mills, should be used in what order to produce the desired shapes of the components [11].

On the other hand, construction plans present an execution strategy. Temporary facilities as part of plans often assist the construction activities conducted by workers and equipment. Project locations, times, and durations which require temporary facilities should be defined before they are needed in the field. Materials for temporary facilities therefore should be readily available since on time installation and avoidance of pre-mature dismantlement are keys to a successful project. As mentioned by many practitioners, temporary facilities should be designed with the same level of detail as the permanent structures to avoid schedule delay and additional costs. They should also comply with regulatory design requirements and best practices. The plan should include approaches to optimize the uses of temporary facilities. The examples of optimization are maximization of sharing of scaffolding between multiple tasks [12] and minimization of formwork system elements which require customized design [13]. Any error in planning temporary facilities can eventually lead to productivity losses and safety issues.

In order to utilize these temporary facilities safely and effectively, the construction industry currently focuses on checking regulations and guidelines provided by OSHA. Construction companies already apply advanced technology, for example, many construction projects utilize model-based technology such as BIM to incorporate major temporary facilities into their construction plans. For the construction project of the University of Baltimore's Law School, a contractor utilized three-dimensional (3D) modeling of formwork systems and scaffolding systems. By doing so, scaffolding systems for floor structures were created and inserted into the main building model [14,15]. Other contractors created a set of parametric formwork system models [16]. As reported, when parametric models are utilized in a project, savings in cost and time were achieved by reducing manual efforts and using the accurate 3D visualization of the formwork designs. During the construction of the Tokyo Sky Tree, the contractor inserted maintenance scaffolding and ladders into the tower model for construction simulation [17]. Eastman et al. [18] introduced many other industry case studies for incorporating temporary facilities such as tower cranes and scaffolding in BIM-based construction planning. As already experienced, the development of realistic construction planning, accurate quantity take-offs, accurate evaluation of constructability and construction safety, and better communication facilitated by