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Model-based space planning for temporary structures using simulation-based multi-objective programming

Haifeng Jin [a,b,*], Mohammad Nahangi [c], Paul M. Goodrum [b], Yongbo Yuan [a]

[a] Department of Construction Management, Dalian University of Technology, Dalian, Liaoning, China
[b] Department of Civil, Environmental, and Architectural Engineering, University of Colorado at Boulder, Boulder, CO, USA
[c] Department of Civil Engineering, University of Toronto, Toronto, ON, Canada

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ABSTRACT

Construction trades need to share temporary structures to increase the output of direct work while controlling the labor input of indirect work. The purpose of this research is to develop a framework to determine the optimal location of temporary structures in a computerized practical manner for piping construction projects. Based on the spatial relationship between work envelope and scaffolding placement requirements, this paper presents the optimization model in two phases: the simulation-based optimization model and a multi-attribute utility (MAU) based alternative selection model. A multi-objective optimization model is established to improve scaffolding availability among multiple activities while maximizing piping crew productivity. The multi-attribute utility model is employed to handle the uncertainty of the assessment weights on the attributes to illustrate the preference of decision makers among different scaffolding placement alternatives obtained from the first phase. The approach was validated in a piping module, which provided superintendents and space planners with an effective decision-making tool among possible scaffolding alternatives in piping construction. The proposed optimization technique is an alternative methodology for solving the productivity-tasks-scaffolding trade-off problem, which further revolutionizes the spatial coordination process of workspace management and temporary structure planning.

1. Introduction

Labor productivity in the United States has declined from a macroeconomic perspective since 1960s [1]. Construction labor productivity can be improved through effective management systems, which affects the ability of construction managers to plan, schedule, and direct jobsite activities [2–4]. Available workspaces are one of the key factors which significantly affect the labor productivity and the efficiency of construction projects [5–11]. However, compared to other resource requirements, space requirements of labor, equipment, and materials change over time [12]. Space planners of a construction project need to identify the workspace requirements and make sure the labor productivity is not reduced by insufficient planning. Workspace requirements consist of multiple workspaces needed by hundreds of activities, which is project-specific [7,13]. To execute tasks, crews should take advantage of temporary structures, which provide them with essential workspace throughout the construction process. Temporary structures are one of the most important factors to influence labor productivity and the other output of work crews.

Scaffolding systems, as one of the most common temporary structures in construction, are used to provide access areas for buildings and decorating structures taller than people who work on them. According to a research study conducted by the Construction Industry Institute (CII), one of the top four primary cost categories is the utilization of temporary structures, which belongs to indirect construction costs [14]. The results also show that the 56 owner and contractor companies consider scaffolding systems as one of the most challenging and wasteful component among the 16 subcategories of indirect construction cost. There is a need to optimize space planning, design and utilization of scaffolding system for multiple trades on site [15].

With a lack of front-end planning and management, temporary structures are installed based on human experiences and judgement, which leads to insufficient space planning and low productivity [16]. During construction, the occupied workspace may change dynamically in 3D space and time, but once the scaffolding system is set up, it remains fixed throughout a construction period.

* Corresponding author at: Department of Construction Management, Dalian University of Technology, Dalian, Liaoning, China.
E-mail address: haifeng.jin@colorado.edu (H. Jin).

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Therefore, there is a need to analyze the execution workspace requirements of all the tasks in the design phase and conduct an advanced temporary structure planning process. Meanwhile, most temporary structures do not appear in the design drawings or software designs. The process of planning the temporary structures is still experience-based and labor-intensive [17], but little attention has been given to the space planning and location optimization of temporary structures. To overcome the drawbacks of the manual planning process, the industry needs an effective and automated space planning approach for temporary structures to improve the labor productivity and control indirect work cost.

This paper discusses the spatial relationship between workspace and temporary structures and presents a two-phase multi-objective optimization methodology to support temporary structure planning, where geometric reasoning and rule-based simulation approaches have been developed. Based on geometric reasoning to transform the spatial optimization problem to a multi-objective model for scaffolding plan generation, the emphasis is placed on the optimization of the number of scaffolding levels and the height of each level. In the first phase, we propose a simulation-based optimization approach to search for the optimal plan for a given number of scaffolding levels, from 1-level alternative, 2-level alternative to the maximum-level alternative. Through the simulation runs, the results generate a set of feasible alternatives for scaffolding platform placement while the labor productivity criterion and the number of unsupported tasks criterion are optimized. In the second phase, the multi-attribute utility (MAU) theory is incorporated to handle the uncertainty of assessment weights on multiple attributes. Considering the scaffolding labor input, which represents the indirect work input, the MAU-based weight sensitivity is employed in the trade-off problem to help planners select the most preferred plan among a set of alternatives generated from the first phase. The framework as well as the justification of the proposed methodology are extensively described in this paper.

2. Background

The architecture, engineering and construction (AEC) industry is in need of an approach for space optimization in temporary structure planning. To achieve effective management of space planning on the jobsite, numerous studies have been performed in several industries.

2.1. Current status of workspace planning and temporary structure planning

In industrial practices, such as manufacturing and construction, there have been approaches attempting to manage and optimize the complicated workspace. In the manufacturing industry, research have been focused on the spatial optimization of industrial workplaces with consideration of task planning, labor productivity and comfort [18,19]. In robot workplace design optimization and task planning, Aly et al. [20] developed a computational algorithm to optimize robot workspace in flexible manufacturing systems using genetic algorithms. For human-robot task planning considering the design of the workplace, Tsarouchi et al. [21] presented a multi-criteria decision-making framework using analytical models and simulation techniques for the evaluation of workplace optimization. In terms of higher productivity [22,23] and better office workplace design [24,25], rule-based approaches [26–28], neural network [29], knowledge-based system [30] and simulation-based tools [31] are integrated to determine the optimal workspace. The aim of such optimization, from experience-based design to optimization design, is to enable work crew to execute with their most productive postures and improve their work efficiency. Meanwhile, adequate workspace, comfortable work height and visual requirement are taken into account [32]. These techniques assisted designers to optimize the parameters of workplace design, which achieves a significantly improved balance between the workspace demand and the workplace requirements.

In the construction industry, previous studies on workspace planning mainly focus on workspace identification, generation, allocation, interference and conflict analysis. To provide the labor crews with a more productive working environment, the workspace knowledge can be applied and analyzed by the temporary structure planners.

Depending on the features of construction design, engineering method and the involved activities, the workspace of the same construction project can be interpreted in multiple perspectives. For multistory buildings, Thabet and Beliveau [8] identified the workspace parameters and proposed a model to define and quantify the workspace demand and availability. The types of workspace and the typical patterns of space use were defined by Riley and Sanvido [33]. Based on the workspace identification and definition, the mechanism of automatic workspace generation was presented by Akinci et al. [12,34]. In addition, they developed a workplanner space generator (i.e. 4D SpaceGen), which automatically generates workspace for each object in ad-hoc 4D environment. Dawood and Mallasi [10] presented a critical space-time analysis (CSA) approach and developed PECASO (patterns execution and critical analysis of sitespace organization) 4D simulator to quantify workspace congestion and identify workspace conflicts. Bannier et al. [35] presented a framework to identify the work envelope requirements through in-depth interviews with superintendents and integrated the workspace requirements with anthropomorphic characteristics for different types of tasks in piping and steel trades. These studies provide practical frameworks to enable the automation of workspace representation and conflict analysis.

In recent years, scaffolding planning and optimization, as one part of temporary structure planning in construction, has drawn more attention from various researchers. It is crucial to place the scaffolding system with the consideration of maximization the share ability among multiple tasks [36] and minimization of formwork system elements which requires customized design [37]. A taxonomy was formalized by Kim and Fischer [38] based on the action features to select appropriate temporary structure for different situations. Although their focus was on the automation in temporary structure type selection, they provided an effective approach to evaluate and analyze the geometric condition based on the spatial relationship between work face and the based surface. Kim and Teizer [15] presented a framework to automatically plan the scaffolding system and generate a scaffolding system in a commercially-available BIM software. Kim and Cho [39] further presented a feature lexicon and developed a semiautomated computer system to select the appropriate scaffolding system. Kim et al. [40] identified the geometric and action conditions affecting temporary structure share ability and formalized a computer application (Temporary Structure-Planning Generator, TSPG) to generate multiple sharing options. These valuable studies set the stage for the more advanced computational temporary structure optimization process.

2.2. Computer-assisted approaches in construction management

To date, various computerized approaches and visualization tools are used for effective and efficient construction management, such as simulation-based method, rule-based method, knowledge-based system, and artificial intelligence.

As an effective method in construction for resource allocation and space planning, simulation-based approach is widely used.