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A hybrid simulation approach for quantitatively analyzing the impact of facility size on construction projects

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ABSTRACT

Sizing temporary facilities is a crucial task in construction site layout planning due to its significant impact on project productivity and cost. This paper describes a simulation-based approach for modeling the size of facilities that temporarily contain materials in construction projects. Different methods have been introduced for estimating the required size of this kind of facility; however, space limitations, particularly on congested sites, may not allow the planner to allocate the estimated space to the facilities. This study aims at quantitatively analyzing the impact of facility size on the project and modeling the managerial corrective actions to remedy the space shortage in facilities. To this end, a hybrid discrete-continuous simulation technique is adopted. Simulation is superior in modeling dynamic interactions between variables as well as modeling construction processes with inherent uncertainties. The combination of discrete and continuous simulation is used to enhance accuracy and model the project at both operational level (i.e., activity level with higher level of detail) to estimate production rate, and strategic level (i.e., macro level with lower level of detail) to account for some construction planning decisions such as material management variables. The novelty of this study is analyzing the impact of facility size on the project time and cost, while managerial actions taken to resolve space shortages are modeled, and interdependent influencing parameters of the different disciplines, such as site layout, material management, logistics, and construction process planning are integrated in a unified model. The applicability and suitability of the proposed approach is demonstrated in layout planning of a tunneling project site.

1. Introduction

Identifying the size of temporary facilities is a crucial task in the site layout planning stage of construction projects. While the size of some facilities (e.g., batch plants and equipment) is predetermined and fixed, the size of other facilities (e.g., material laydowns and stock piles) is variable and should be determined in this stage. In construction projects, variable-size facilities are mostly related to facilities temporarily containing materials. Hence, they can be referred to as "material-dependent facilities." This study focuses on modeling the size of material-dependent facilities due to its significant impacts on project productivity and cost.

Facilities occupy space on sites. Space is an important resource in construction projects [9], so this resource should be used efficiently through optimum facility size planning. On small sites, sizing facilities is more critical because of limitations on the space and the consequences of inaccurate estimation of facility size. In general, improperly sizing facilities imposes congestion and space conflicts, which adversely influences the productivity and safety of projects [2,8,27]. Specifically, underestimation of the size of material-dependent facilities causes space shortage for that facility, which can result in loss of productivity and incur extra cost for resolving the encountered problems. For example, insufficient size allocation of a material storage can cause lower productivity in many ways, such as: interrupting material flow when there is no space for offloading materials, and spending more time on finding and handling materials when the storage is congested. On small sites, however, insufficient space for material-dependent facilities may be unavoidable, and in these cases, the planner should alter some construction planning decisions (e.g., material delivery plan) to reduce the need for space on the site. As such, considering those variables as well as the corrective actions to resolve space shortages is vital in modeling facility size. On the other hand, overestimation of facility size can impose spatial conflicts and lack of space for the other facilities. On large sites where space is not limited, facility installation and maintenance costs are the drivers of facility size. As an objective of this research, the impacts of material-dependent facility size on different aspects of a project such as productivity, material flow, size of other facilities and project cost and time are quantitatively evaluated.

Although sizing facilities is considered a part of site layout planning tasks [26], most studies in construction site layout planning focused on

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optimizing the position of the facilities (e.g., (Ning et al., [13,14,28], and less attention was paid to efficiently planning the size of the facilities. In the context of site layout planning, Elbeltagi and Hegazy [6] proposed a knowledge-based method to identify required areas of a number of temporary facilities using IF-THEN rules. The implemented rules were defined on the basis of personnel requirements, estimated quantity of work, production rate of resources, availability of site space, and cost but did not account for possible variation of these parameters throughout the project. In space scheduling, Zouein and Tommelein [32] categorized the profile of the space needs for facilities into resource independent, which was fixed, and resource dependent which was either fixed or variable over the project. For the variable profiles, space needs might decrease linearly or fluctuate between minimum and maximum levels as the corresponding activities progress, which are over-simplified assumptions. The size of the facilities is also addressed in the unequal-area facility layout problems (e.g., [30] and [12], in which facilities are assigned to predetermined locations, and due to the size constraints, large facilities cannot be assigned to small size locations. Although the size of the facilities is considered in this assignment, this approach cannot quantitatively assess the impact of the facility size on the project time or cost.

Facility size and required space for facilities were noted in other contexts, such as time–space conflict analysis [1], integration of schedule and space planning [31], and workspace management [4]. In these studies, the influence of spatial conflicts and the methods to manage them were discussed; however, the sizing of facilities was not presented.

In one of the most recent studies, Said and El-Rayes [22] developed a model for optimizing material procurement decision variables and material storage layout to achieve minimum logistics costs. In their model, material demand rates and material procurement decision variables influence the required size of the material storage area determined heuristically. Despite the novelty of this study, the uncertainties in construction projects could have been taken into account for estimating the material demand rate, which was based on a certain construction plan in the model.

For modeling dynamics and uncertainties inherent in construction projects, simulation has often been utilized in the literature (e.g., [25] and [21]. In relevant research, Ebrahimy et al. [5] used simulation to model supply chain management in tunneling construction, and evaluated the effect of space shortage for storing concrete segment liners, located on supplier's sites and the construction site, on the project time. This research demonstrated the capability of simulation to model storage capacity and the effect of space shortage on the project time. Alanjari et al. [3] integrated simulation with genetic algorithm to optimize material placement layout in yard laydowns. RazaviAlavi et al. [17] also used a simulation-based approach to more accurately model variation of the space required for facilities throughout construction projects. However, these studies overlooked the site layout constraints in sizing facilities, and could not model the situation in which the required space for facilities is not available on the site. Cellular automata (CA) is another technique that can be used for modeling space represented by uniform grids. Zhang et al. [29] used CA to model space resources in construction simulation, analyze spatial conflicts, and visualize the occupied space on construction sites. Agent-based simulation can also be used to model some features in layout planning such as workers' movements. Said et al. [23] used agent-based simulation to evaluate performance of labor emergency evacuation plans considering geometry of the site.

Managerial corrective actions taken to remedy encountered problems need to be modeled to represent real-world projects [11]. This issue is essential in layout planning on congested sites because the planners may not be able to provide the required space for all facilities. Consequently, they may shrink the size of some facilities and take managerial actions when lacking space on the site. According to the main objective of this research, a simulation-based approach is adopted to quantitatively analyze the impact of size of material-dependent facilities on the project time and cost, model managerial actions and dynamic interactions between the interdependent variables, and consider uncertainties in construction projects. A combination of discrete event simulation (DES) and continuous simulation (CS) is used for more accurately modeling material flow and managerial actions. The proposed approach also aims to consider site layout constraints, and planning decisions of different disciplines, such as construction operation planning, material management and logistics, in a unified model.

The following sections describe the research methodology and the approach for modeling facility size and managerial actions. Next, a case study is presented to demonstrate implementation of the developed approach. In the last section, the paper is summarized and the conclusion is drawn.

2. Research methodology

For sizing material-dependent facilities, the amount of material placed within a facility should be accounted for throughout the project time. To this end, material flow should be modeled to identify the quantity of material and time that materials come into the facility and leave the facility (i.e., material inflow to the facility and outflow from the facility). Although it is difficult to introduce a generic model for material flow in construction projects, the production of the system is always part of the model. To outline the significance of the system production, material-dependent facilities on the construction sites are categorized into three groups:

- Group I: For this group, only the material inflow of the facility comes from the system production, which is very common in earthmoving projects. For instance, a spoil pile can be classified as Group I where its inflow is produced from the excavation executed in the construction process. Then the soil may be hauled from the site by trucks to an off-site dumping area.
- Group II: For this group, only the material outflow of the facility is to be consumed in the production process of the system, which is very common when the material is delivered to the site and consumed throughout the project. In steel structure projects, for example, steel materials are purchased from a supplier and stacked on the site to be erected in the project, so the steel material storage can be considered Group II.
- Group III: For this group, the material inflow comes from the system production and the material outflow goes to be consumed in the production of the same system or another system. For instance, the intermediate storage containing modules produced in the module yard and going to be installed on construction sites can be categorized as Group III. In this example, the material inflow comes from the production of the module yard, and material outflow goes to the production of the construction site. An example of the same production system for both inflow and outflow is the temporary soil stockpile maintaining the soil excavated in pipeline construction to be used in filling of the excavation after installing the pipes.

As a result of this classification, the accuracy of the production rate estimate is identified as a key component in accurately sizing any material-dependent facilities. In addition, the quantity of available material in a facility can influence the production. For instance, when the material storage is stock-out, or its capacity is full, it can interrupt the production rate. This mutual effect, which is mostly oversight in the existing methods, is important to be modeled. In construction projects, estimating production rate is a complicated process due to the dynamic nature of construction and complexity of construction operations. In particular, the construction uncertainties cause production rate variations, which make it difficult to capture the interaction between production rate and other variables like material flow and facility size. To overcome