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Automated system for form layout to increase the proportion of standard forms and improve work efficiency

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ABSTRACT

This paper proposes an automated form layout system that: 1) arranges standard and nonstandard slab-forms automatically to improve work efficiency, and 2) maximizes the proportion of standard forms to reduce manufacturing cost. To accomplish this, the proposed system considers factors such as building shape, connected areas, beams and shores, form size, boundary lines, and layout direction. When applied to six previous construction cases, the proposed layout system is shown to produce a higher proportion of standard to nonstandard form (a maximum of about 23%) than existing methods, which rely on a combination of automated and manual approaches. Furthermore, no more than 31 min are required to determine the layout using the proposed automated system. The proposed system can improve the operational efficiency of form layout, reduce form manufacturing cost, and improve the efficiency of form installation work by increasing the proportion of standard forms used.

1. Introduction

During the construction of buildings, the cost of formwork consumes about 10% of the total construction cost [1–3]. The importance of form layout planning has steadily increased due to the increase in the use of nonstandard forms required to construct buildings with irregular shapes. This increased number of irregularly shaped buildings affects the time and effort required for designers to determine form layout [4], because they must attempt to maximize the proportion of standard form and arrange the nonstandard form with consideration of the ease with which it can be constructed and installed.

These challenges suggest that the development of an automated form layout system would not only help to maximize the proportion of standard form, but also improve the work efficiency of the form layout designer. Because the manufacturing costs of standard form are lower and the labor productivity is higher than for nonstandard form, the use of such an automated system may also contribute to a reduction in construction cost [5]. Furthermore, nonstandard forms are often applicable only to a unique area, and are therefore useless if a customer changes an order, or if there are design errors; however, standard form has a wide range of applications and can be reused on other projects even if the original order is changed.

Most previous studies of formwork are focused on methods for selecting a suitable form [1,6–12], determining an appropriate form layout for a given structure [13–18], developing novel form or improving existing form [19–21], and improving layout productivity [22–25]. While several previous studies and form-production companies have developed automated systems to lay out forms and to increase the proportion of standard forms used, these systems are limited as follows [4,5,26,27]:

- Existing automated form-layout systems consider only forms provided by the form company that developed them.
- An expert still must plan the layout of nonstandard forms manually; the task of designing a layout for such cases remains difficult and time consuming.
- When multiple types of standard and nonstandard forms are used, the expert must determine the proportions of each form type.
- Layout directions (from left to right, from top to bottom, and the direction of the width and length) are determined based on expert judgement.
- The expert must manually arrange all connections, e.g., slab to wall or slab to column.

To address these current limitations, the purpose of this study is to develop an automated form layout system that reduces the time and manual effort required for form layout, and maximizes the usage of standard forms based on user requirements. Of the many different types

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of formwork, this study focuses on the layout of slab formwork as this is often the most critical and time-consuming layout in the concrete construction process [5].

This study is composed of two stages. First, the factors that impact form layout are presented, and the characteristics of the layout algorithm and the system developed to improve the existing layout methods are described. Then the criteria used to evaluate the effectiveness of the proposed system are described, and the system is applied to six previous construction cases to verify its effectiveness.

2. Literature review

Previous studies related to formwork can be classified into methods to select formwork type [1,6–12], methods to arrange the form and components (such as sheathing, studs, wales, and ties) to ensure structural stability [13–18], methods to develop formwork systems using both new and improved systems [19–21], and methods to improve constructability and productivity while reducing cost [22–25]. However, to the best of our knowledge, to date there have been no studies into methods for generating a form layout automatically to improve the proportion of standard form.

Previous studies related to methods used to select formwork types can be classified according to whether they account for the relative importance of various selection criteria in determining the layout [8,9,11,12] or instead use neural networks, boosted decision trees, or quantity and cost analysis to determine layout from a basic set of impact factors [1,6–12]. The impact factors used in previous studies include geographical location, building characteristics, and construction techniques. These factors can be broadly classified into building design, job specification, site characteristic, and supporting organization factors. Although some of these factors can be applied to develop the currently proposed system, because the proposed system attempts to automatically maximize the proportion of standard form rather than simply selecting and arranging formwork types, it is difficult to apply many of the other factors. A brief summary of the different factors used as selection criteria in previous formwork layout systems follows:

- Building design: includes slab type, lateral load supporting system, structural type, building height, building shape, degree of repetition, number of floors, area of typical floor per zone, and typical floor cycle.
- Job specification: concrete finish, construction speed.
- Site characteristics: area use, weather conditions, accessibility to site, availability of staging area, and presence of surrounding restrictions such as adjacent buildings, power lines, or busy streets.
- Supporting organization: available capital and labor, hoisting equipment availability, home office support, and supporting yard facilities.

In terms of structural stability, previous formwork layout studies largely focus on developing a system to reduce material waste [13] or proposing design criteria such as loading, inclination of form, and distance between components [14–18]. Christian and Mir [13] developed a system that analyzed the concrete pressure, stud spacing, wale spacing, and form tie suitability and spacing. Additionally, they analyzed the formwork material and cost calculations based on wall dimensions, selected sheathing, studs, wales, and ties, and adjusted formwork parameters to reduce material waste. Most previous studies, like the current study, attempt to reduce the material waste by maximizing opportunities for repetitive use. However, the degree of waste reduction is typically different from that achieved in this study as most previous waste reductions are accomplished by optimizing a form layout design from an overall economic perspective rather than by purely increasing the proportion of standard forms used. Karshenas [14] analyzed the physical conditions of formwork members, installation inaccuracies, shore-compressive strengths, and the bending and shear strengths of formwork stringers and joists. Shapira [15] analyzed the impacts of the distance between formwork components such as sheathing, joists, and stringers, using the results of the analysis to propose design criteria. Ringwald [16] and Tah and Price [17] proposed design criteria for typical and extreme loading, and Gallego et al. [18] proposed design criteria for the analysis of the relative motion between fresh concrete and the formwork walls of complexly shaped buildings. These previous studies all propose various design criteria to improve the structural stability of formwork, but do not propose any design criteria attempting to improve the proportion of standard form used.

Some previous studies have developed new or improved formwork types focused on increasing productivity, quality, and safety, and reducing cost [19–21]. Lee et al. [19] developed a non-shored top-down hanging-type formwork system that reduces required excavation and improves the quality of underground concrete. Kim et al. [20] developed an automated lifting system using a combination of construction hoists and table formwork to reduce the additional work and cost required for formwork assembly and installation, and to improve work crew productivity. Shaffer [21] developed a robotic formwork system to improve labor safety, mobility, and variability of forms, and to reduce costs associated with installation and breakdown. These previous studies are often quite similar to the current study as they aim to improve constructability, productivity, and economic performance, frequently by increasing in the proportion of standard form used. However, the development of new types of formwork is outside the scope of the current study, which instead uses a selected type of already extant standard form for optimization.

Several previous studies have proposed methods for the reduction of construction cost using constructability reviews and productivity measurements [22–25]. Jiang and Leicht [22] and Lee et al. [24] proposed methods to analyze labor productivity and to review the constructability of formwork using building information modeling (BIM). Huang et al. [23] analyzed the impact of variations in form sets, cranes, and labor crews on productivity and cost-efficiency using a simulation tool (MicroCYCLONE). Jarkas [25] proposed impact factors for constructability (grid patterns, variability of column sizes, repetition, total and average shutter size, and geometry of columns) and provided the impact of those factors on labor productivity. Mansuri et al. [28] proposed a method for reducing form waste using the required amount of formwork and an inventory list based on BIM. Benoist et al. [29] proposed a method for minimizing the amount of shuttering materials (a typical component of formwork) used. Dikmen and Sonmez [30] proposed a method that analyzed the number of man-hours required for formwork activities using artificial neural networks. These previous studies are similar to this study in terms of the improvements realized through the reuse of formwork. However, this study is different as the proposed system is developed to maximize the use of a standard form, and not a set of standardized form components. Hanna and Senouci [31] have proposed a method to determine the number and size of form panels required for a job based on their geometry, which is quite similar to this study. However, Hanna and Senouci also attempted to reduce the wall shuttering and rental costs, which are not addressed in this paper.

In the next section, the impact factors on form layout are derived based on several previous studies and then determined through surveys and interviews with experts.

3. Impact factors on form layout

The impact factors on form layout are identified based on a review of the literature [4,32] as well as from interviews and surveys with 23 form layout experts. Five of the experts had over 15 years of experience, six of them had between 10 and 14 years, six of them had between 5 and 9 years, and six experts had less than 5 years of experience. These impact factors can be divided into factors applicable to building shapes, connected areas, beams and shores, the layout of standard forms, and