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Exterior prefabricated panelized walls platform optimization

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ABSTRACT

Panelized wall system (PWS) is an effective offsite prefabrication approach that provides higher flexibility and customization power compared to modular construction. Product platform is an industrial engineering approach that can help in managing the panels' layout and component proliferation in the effort to comply with varying design requirements. Accordingly, this paper presents the development, implementation, and validation of a new exterior panelized walls platform optimization (EPWPO) model that optimizes the tradeoff between minimizing the total fabrication cost of the panels and minimizing the resulting design deviation from enforcing common platform designs for the panels. Two new metrics were developed to quantify the two conflicting objectives of panel platform design: total fabrication cost (*TFC*) and design deviation index (DDI). New computational algorithms were developed to automate the functions of panel elements geometry manipulation, structural analysis, and structural design in conjunction with the optimization process. The performance of the EPWPO model was illustrated using an application example of the fabrication of the exterior wall panels of a public school. Two analyses were performed to investigate the dependence of the model results on the platform configuration input and the degree of wall length tolerances.

1. Introduction

Offsite prefabrication/preassembly (OPP) has been proposed by construction researchers and professionals as an effective approach to industrialize construction projects delivery and achieve higher performance levels similar to consumer product and automobile industries. OPP depends on the lean concept of moving the work to the workers in a controlled production environment, afterwards building components and systems are assembled and transported to the site for installation. OPP results in quality and efficiency improvements due to better working conditions, automation possibilities, and opportunities for concurrent onsite and offsite schedules [7,12].

Panelized wall systems have been considered by the industry as a viable building OPP system due to its flexibility in constructing exterior building façade and interior partitions offsite under varying design requirements. Panelized wall system (PWS) involves dividing the wall length into panels that are fabricated using either wood or metal studs, with panel widths usually controlled by trucking width that does not allow special transportation permits (around 10 ft. in the USA). Wall panels can be fabricated for either interior partition or exterior façade, with a height ranging between one to two floors. PWS is classified as a non-volumetric pre-assembly OPP approach [9,19], which provides more flexibility in satisfying varying design requirements than the opposite strategic OPP approach, modular building [7].

Despite the design flexibility of PWS, its production efficiency deteriorates with the increase of panel component and layout configuration proliferation to satisfy varying design requirements. There is a critical tradeoff between satisfying varying customer design requirements and maintaining an acceptable level of design commonality between the fabricated assemblies [33,39], which in this case are the wall panels. Design variations can lead to unnecessary design effort and inefficiencies in the fabrication process and material supply management [17]. Also, it is a challenging task to maintain commonality between the wall panels and the economics of scale with the very strict design requirements and variations between the panels in the same project and between projects [6]. Lean production is not relevant in dealing with such commonality-distinctiveness tradeoff due to its main focus on eliminating waste and reducing variability [52]. Instead, mass customization (MC) principles [17,47] are better suited for the construction industry, which mostly deals with engineer-to-order (ETO) products/assemblies [10].

As such, this research study was motivated by the need to investigate the application of flexible mass customization design and production principals that allow for better management of the critical tradeoff between production efficient and design flexibility in exterior panelized wall systems.

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2. Theory and literature review

2.1. Mass customization and platform design

Mass customization was investigated intensively in the manufacturing industry that inspired construction engineering and management research to apply its concepts in mainly home and residential construction. Consumer products and automobile manufacturing industries attempted to overcome the commonality-distinctiveness tradeoff by developing new design approaches following the principals of mass customization (MC) [17,41,47,51]. The main goal of MC is to satisfy the unique needs and design requirements of different customers/projects while still being close the efficiencies of mass production [17,45]. A well-known strategy to implement MC is the development of product family architecture [38,41], which involves the design of generic product architectures that can capture commonalities between different products with design features added or changed between products.

2.2. Product platforms

Product platform is an effective family architecture approach that facilitates the reduction of production complexity, cost, time, and flexibility to respond to different design requirements [42]. Product family platform is common to all products and represents the maximum standardization and reusability of components between the products considering the variety in their performance design requirements [35]. Two main architectures have been proposed for product platforms: modular and scalable platforms [35,42]. A modular platform allows the creation of design variants through the addition or removal of modular components that integrate through standardized interfaces [38,40]. On the other hand, a scalable platform allows the change of one or more of its design parameters to create products whose performance changes accordingly to satisfy different customer requirements [31]. Most of reported applications of modular platforms originated from electronic products, while scalable platforms are commonly used in the skeleton and engines of automobiles and aircrafts [42]. Generally, platform design and development go through three main steps [39]: 1) products' requirements are identified through marketing, customer surveys, or technical design standards; 2) commonality between the functions and components of all products are identified; and 3) differentiation plans are generated to achieve design variety with minimal level of disruption to the common platforms.

For manufacturing industries, previous research studies presented qualitative and quantitative approaches to design and optimize product platforms. Martin and Ishii [29] developed a design for variety (DFV) methodology that utilizes two metrics to evaluate the product architecture design. The first index is the generational variety index that is used to evaluate the expected redesign effort to adjust the product architecture design for possible future performance variation. The second index is the coupling index that is used to measure the interdependencies between the product components that may complicate future redesign plans. Robertson and Ulrich [39] presented a product platform planning approach that is based on the need to balance between the product architecture commonality and its distinctiveness. The proposed platform plan includes developing three main sub-plans: product plan, commonality plan, and differentiation plan. Simpson et al. [41] developed a product variety tradeoff evaluation methodology for assessing possible product platform designs with different degrees of commonality, utilizing two main indices: non-commonality index (NCI) and performance deviation index (PDI). Jiao and Tseng [17] developed another set of indices with a focus on quantifying the commonality in product components and manufacturing process. Messac et al. [31] developed a single-stage physical programming model to optimize scale-based platform products, which simultaneously considers scaling the dimensions of an engine platform and its product family variants. Fujita [48] developed an optimization formulation for optimizing the product design to maximize its variety under fixed product architecture. This formulation includes three main sub-problems: attribute assignment within each module, modules combination, and their simultaneous design. Nayak et al. [35] developed a variation-based platform design method (VBPDM) to analyze the tradeoff between minimizing platform variations and maximize the range of satisfying functional requirements. Rai and Allada [38] developed a two-step approach to support the problem of product family design that involves: 1) performing a multi-objective multi-agent optimization to maximize the Pareto tradeoff between various design technical requirements; 2) applying a post–optimization analysis to determine optimal platform level to increase product variety while minimizing its quality loss. Simpson and D'Souza [43] developed a multi-objective optimization approach for product family design that simultaneously designs the product platform and its family products. The optimization approach employs genetic algorithms (GA) to generate tradeoffs between product commonality and distinctiveness, which was illustrated using an aircraft design example. Khajavirad et al. [20] proposed a decomposed multi-objective GA model to concurrently optimize the platform selection, platform design, and variant design for product family design problems. The decomposed approach utilizes a single-stage two-level formulation to generate better optimization tradeoff between products commonality and performance.

2.3. Construction mass customization

Mass customization and platform design research in the construction engineering and management area focused on homebuilding due to the homogeneity of housing as a product and market demand. Veenstra et al. [49] proposed a methodology to develop product platform architecture for the Dutch homebuilding market, following the design for variety framework [29]. Nahmens and Mullens [34] studied the role of lean production in increased product variety in homebuilding companies. The case study findings suggested that lean principals (such as continuous flow, flow system, etc.) are still valid concepts for handling increased range of product choice. This conclusion conflicts with other studies [10,52], as increased design variety necessitates the implementation of agile flexible production systems. Persson et al. [37] applied a case study approach to analyze the use of information technology to facilitate the development and communication of platforms in industrialized house construction. da Rocha and Kemmer [4] proposed a methodology for delayed product differential (DPD) in customizing the design of high-rise apartment buildings. The main focus of this DPD methodology is to postpone the decoupling point (the time when the customer order first affects the supply chain) of the apartment customization to improve the mass customization performance in terms of reduced lead times, design varieties, and production cost. Wikberg et al. [51] proposed the use of hierarchical architectural objects to support the configuration and customization of industrialized homebuilding platforms. Jansson et al. [15] explored the role of experience feedback, knowledge management, and organizational learning in the continuous development and innovation of house building platforms. Other studies [12,22] focused on developing interfacing systems to facilitate the participation of homebuilding customers in the design process of customized houses. These systems utilized web-based and object oriented approaches to allow the customers to configure their future homes under standardized architectural constraints and components. Another set of studies [13,14,16,27] analyzed case studies of the application of platforms and standardized components to customize homes and residential units.

Few studies applied the concepts of mass customization and product platform outside the residential and homebuilding sectors of the industry. Khalili and Chua [21] developed a mixed integer linear programming model to minimize the cost of precast production operations by utilizing the concepts of prefabrication configuration, component groups, and precasting mold adaptability index. Larsson et al. [25]