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Optimization modeling of multi-skilled resources in prefabrication: Theorizing cost analysis of process integration in off-site construction

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ABSTRACT

In advanced manufacturing of building elements, process integration and utilization of multi-skilled resources enhance the flexibility of production networks against variations in demand and resource availability. This research study aims to incorporate the required cost and time for cross-training multi-skilled resources into resource planning computations. Towards this aim, minimizing the cost of utilizing multi-skilled resources in off-site construction is formulated using integer and probabilistic optimization models. Production data of two prefabrication networks in Brisbane and Melbourne, Australia are used to derive computational results and validate models. The main contribution of this research study is to analyze the costeffectiveness of deploying multi-skilled resources with the aim of improving production flexibility. The modeling methodology and findings are of practical use to off-site manufacturers that experience variations in production demand and resource availability.

1. Introduction

Off-site construction has been recognized as offering significant advantages over site-built construction [1]. These advantages include but are not limited to shortened completion times [2], enhanced quality [3], reduced costs [4], and better worker safety [5]. However, prefabrication industry is criticized as the replica of the traditional site-built construction in assigning operations to individually specialized work teams [6,7]. A simple volumetric module (as shown in Fig. 1), engages more than a dozen of trades that often work consecutively due to spatial and temporal restrictions. These trades include but are not limited to carpenter, joiner, caulker, tiler, water proofer, plumber, mechanical contractor, plasterer, painter, and electrician. The current organization of resources results in excessive fragmentation in construction, also known as parade of trades [8,9].

When assigning processes to individually specialized resources, longer process times of critical (bottleneck) operations determine the completion time of construction production [10]. Resource multiskilling results in process integration and increases production flexibility and productivity [11,12]. In this paper, the two terms of multiskilling and process integration have been used interchangeably. A multi-skilled resource is defined by having one or more additional skills to complete processes rather than their primary task [13]. The most intuitive architecture for process integration is bottleneck skill-balancing [14,15], where underutilized resources are trained to help overutilized resources (bottlenecks). Assuming that frame assembly is the bottleneck process in a prefabrication plant, other resources such as carpenters can be trained to assist in the framing assembly [16,17].

Process integration can also be implemented using the adjacent skill-chaining architecture [18,19]. In this architecture, every resource is capable of performing their primary process as well as the next immediate process. Adjacent skill-chaining has proved its capability to prevent work starvations and overloads in production networks with unbalanced processing times [20]. The most effective architecture for utilizing multi-skilled resources is full skill-chaining where resources are cross-trained to undertake every and each process [21]. This strategy has substantial potential to increase the production flexibility in the pseudo manufacturing environment of off-site construction [22].

Despite benefits of multiskilling, it complicates the process of resource planning [23,24]. The problem of multi-skilled resource planning in off-site construction remains nontrivial to solve. According to Gomar et al. [25] and Liu and Wang [26], this is mainly due to

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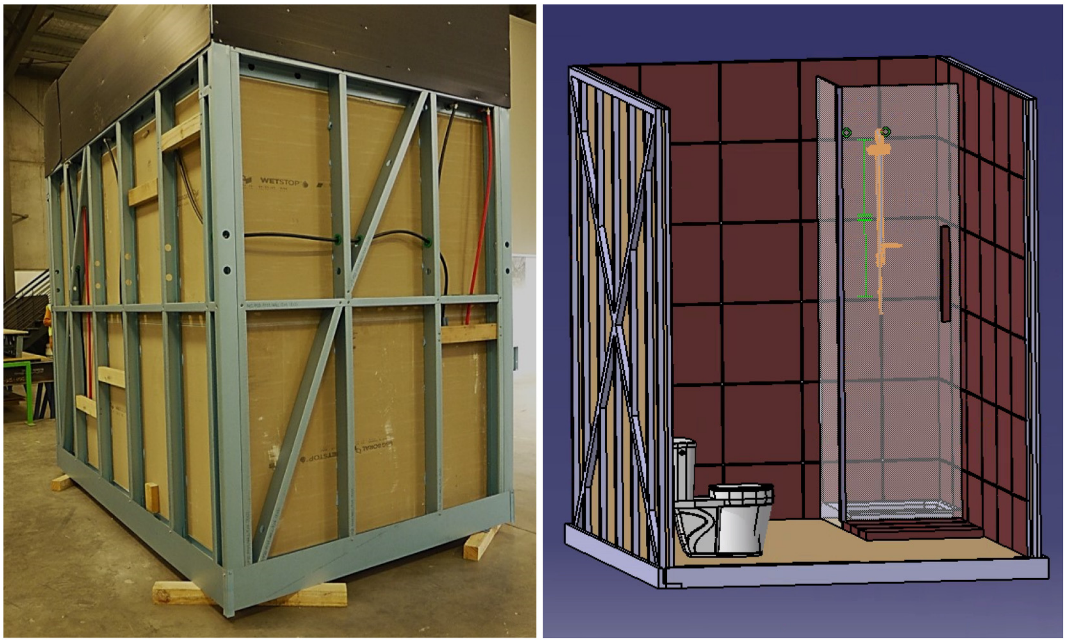

Fig. 1. Volumetric modules manufactured by individually specialized resources.

complexity of production in the pseudo manufacturing environment of off-site construction, especially when multi-skilled resources are deployed.

In order to bridge this gap, the current study formalizes the problem by incorporating the cost and time associated with deployment of multi-skilled resources in off-site construction networks. The paper consists of developing and testing three research hypotheses. Towards this end, computational results of developed models are presented based on empirical research. Following the presentation of findings, possible extensions to this work are discussed.

2. Background

Production systems with multi-skilled resources are more flexible in balancing the workload [27], minimizing capacity imbalance [28], responding to demand variations [29], and coping with absenteeism [30]. Off-site construction provides an ideal environment for deployment of multi-skilled resources as it is a unique hybrid of manufacturing and construction [31,32]. Due to the prevalence of multiskilling in modern industries, extensive studies have been conducted in engineering and construction literature [33–36]. Table 1 provides a summary of utilized modeling approaches in the literature.

The mainstream research on process integration has focused on either minimizing the number of resources for a given completion time [37,38], or minimizing the completion time for a given number of resources [39,40]. Current study, however, analyzes the broader problem of minimizing the process integration cost in real-world off-site construction scenarios. Traditionally, deployment of multi-skilled resources is modeled as a middle-term planning problem with an equal horizon to the actual production period [41,42]. In other words, the period of time over which the planning and actual production takes place is the same. This paper relaxes the aforementioned assumption and recognizes different modeling horizons (timing periods) for resource planning and actual production.

A prevalent assumption in modeling flexible production systems with multi-skilled resources is static demand over the production period [43,44]. In off-site construction, however, this is not a realistic assumption. The intense competition of current marketplace coupled with periods of construction boom and bust, result in significant fluctuations in demand [45,46]. The proposed model in this research analyzes the dynamic demand over the course of production. An important optimization variable in flexible production networks with multi-skilled resources is the time spent on cross-training [47–49]. The proposed optimization model recognizes the time consuming nature of cross-training and the associated cost impact.

Deployment of multi-skilled resources results in balancing the workload and reducing the impact of variations in resource availability [50–53]. However, systems with integrated processes still need to deal

Table 1
Different approaches to model multiskilling in construction.

Modeling approach	Paper title	Authors
Linear programming	Optimal assignment of multi-skilled labour in building construction projects	[86]
	Linear programming approach to optimize strategic investment in the construction workforce	[87]
	Assignment and allocation optimization of partially multi-skilled workforce	[25]
Mixed integer programming	Maximizing labour stability as a sustainability performance indicator in Project scheduling	[88]
	Crew Allocation System for the Masonry Industry	[89]
Heuristic methods	Algorithm for scheduling with multi-skilled constrained resources	[90]
	Augmented heuristic algorithm for multi-skilled resource scheduling	[30]
Meta heuristics and genetic algorithms	Genetic algorithm model in optimizing the use of labour	[91]
	A genetic algorithm-based method for scheduling repetitive construction projects	[92]
Line of balance	Improvised Scheduling Framework Integrating WS, MS, & DS for Repetitive Construction Projects	[93]
	Optimal crew routing for linear repetitive projects using graph theory	[94]
Constraint programming	Optimizing linear project scheduling with multi-skilled crews	[26]

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