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Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction

Mehdrad Arashpour[a,*], Yu Bai[b], Guillermo Aranda-mena[a], Alireza Bab-Hadiashar[c], Reza Hosseini[d], Pushpitha Kalutara[d]

[a] School of Property, Construction and Project Management, RMIT University, 360 Swanston St, Melbourne, VIC 3000, Australia
[b] Department of Civil Engineering, Monash University, 23 College Walk, VIC 3800, Australia
[c] School of Engineering, RMIT University, 360 Swanston St, Melbourne, VIC 3000, Australia
[d] School of Architecture and Built Environment, Deakin University, Geelong, VIC 3220, Australia

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ABSTRACT

Robust supply decision making is critical to the advanced manufacturing of prefabricated products. Previous related research focused on minimizing cost overruns in off-site construction supply networks by optimizing purchasing decisions. However, decision parameters such as strategic preferences to include or exclude certain suppliers and utilization of multi-supplier configurations are yet to be formulated and analytically solved. The proposed optimization models aim to enhance supply network performance with a smaller overall investment. Toward this aim, three research hypotheses on optimization of supply decisions and configurations are developed and tested. A real-world precast panel production project serves as the test bed to demonstrate the effectiveness of the mathematical programming and analyze cost implications of supply related decisions. The modeling method and results contribute to optimal decision making in advanced manufacturing of prefabricated products.

1. Introduction

In the off-site construction domain, technology is increasingly used to create cutting-edge and innovative product and processes [1]. Advanced manufacturing of prefabricated components focuses on making complex and innovative products that are reliable and affordable [2,3]. The required manufacturing process technologies include but are not limited to rapid prototyping [4], intelligent production systems such as robotics [5,6], high performance computing for simulation and control systems [7,8], and innovative use of composite materials [9,10]. Tangible performance measures in advanced manufacturing of building elements can be improved by optimizing decision making in critical areas such as supply configurations [11,12].

Optimizing supply decisions enables off-site manufacturers to achieve high production performance with a smaller supply investment [13,14]. Considering the complexity of supply networks in prefabrication, it is not a trivial task to optimize supply decisions and configuration parameters [15]. As an example, manufacturers of precast wall panels (Fig. 1) utilize a large variety of elements in > 30 main product groups such as rebar, ready-mix concrete, formwork, lifting and installation inserts, and waterproofing materials [16].

Complexity of decision making in advanced manufacturing of prefabricated products is further increased by the presence of uncertainty in supply-related parameters such as supplier reliability [17]. In a common risk mitigation strategy, a multi-supplier configuration is adopted to minimize potential disruptions [18,19]. However, cost implications of adopting multi-supplier configuration in multi-product environment of prefabrication are not clear [20]. Another source of complexity in supply decision making is purchasing strategic preferences and tendency to include or exclude certain suppliers from the network configurations [21]. Such strategic preferences and logical constraints are yet to be analytically modeled and solved in off-site production [22].

The present research aims to optimize supply-related decisions in advanced manufacturing of prefabricated products by developing and testing three research hypotheses. First, the effectiveness of standard operational research approaches such as zero-one (binary) mathematical programming in analyzing supply decisions is tested. Then, strategic preferences in purchasing and resultant cost implications are modeled. Finally, optimization of supply decisions under uncertainty is

* Corresponding author.
E-mail addresses: mehrdad.arashpour@rmit.edu.au (M. Arashpour), yu.bai@monash.edu (Y. Bai), guillermo.aranda-mena@rmit.edu.au (G. Aranda-mena), alireza.bab-hadiashar@rmit.edu.au (A. Bab-Hadiashar), reza.hosseini@deakin.edu.au (R. Hosseini), pushpitha.kalutara@deakin.edu.au (P. Kalutara).

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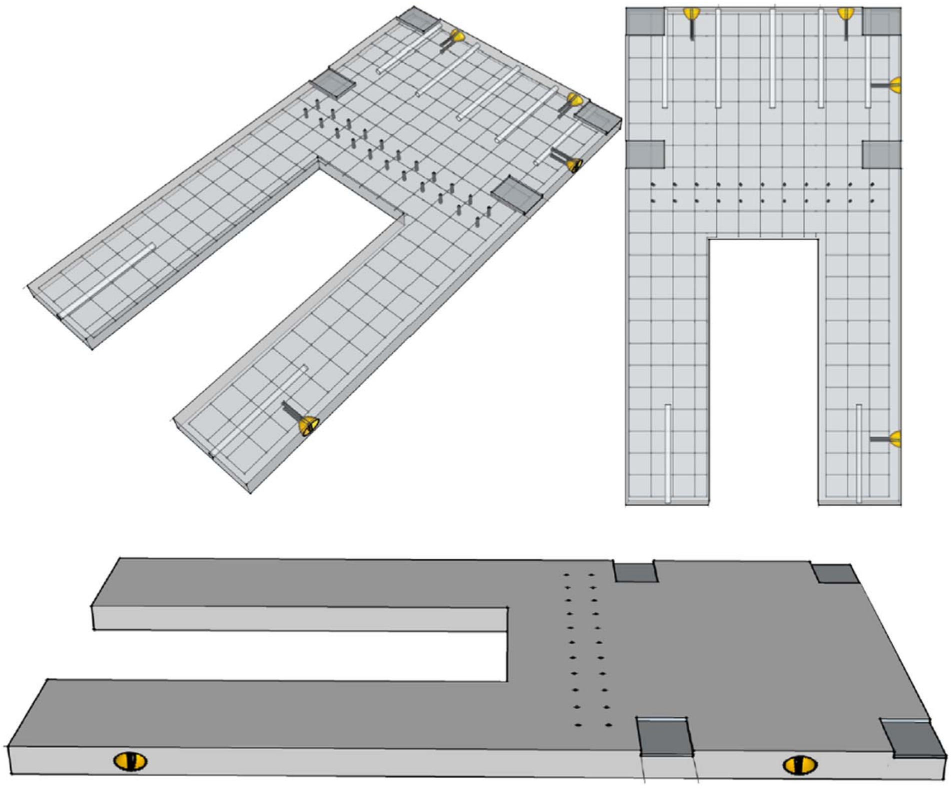

Fig. 1. Prefabricated wall panels and embedded elements.

formulated and cost of adopting multi-supplier configurations to address uncertainty is analyzed.

Background section of the paper provides a review of supply decision making issues followed by supply characteristics in advanced manufacturing of prefabricated products. Sections 3 and 4 explain the modeling framework and formulation of logical constraints. Section 5 discusses the results of testing the three hypotheses. Sections 6 and 7 present research limitations, conclusions and opportunities for future research.

2. Background

2.1. Complexity of supply decision making

Supply decision making is a multi-echelon problem with different dimensions including coordination of multipart purchasing and supplier relations management [23]. There are several factors contributing to the complexity of supply decisions such as production variability [24], purchasing preferences [25], and uncertainty in supplier reliability [26]. Production variability has significant impacts on the whole supply network. By production being behind the schedule, supplier deliveries will build up inventory levels [27] and when production is ahead of the schedule, there will be a shortage of supplied parts [28]. Strategic preferences in purchasing also complicate supply decisions and configuration parameters by converting them to multi-criteria decision making problems [29]. Furthermore, unreliability of suppliers can result in production disruptions and decreasing service levels and customer responsiveness [30].

In order to optimize supply configurations and address the aforementioned issues, the mainstream supply research proposes the use of safety stocks or buffers [31]. Furthermore, standard operational research methods such as linear programming have been extensively used to optimize the size of such buffers [32,33]. Although safety stocks provide a temporary and quick remedy to supply stock outs, they are wasteful and not aligned with principles of lean production [34]. Size optimization of safety stocks requires frequent analysis and adjustment especially when the production is exposed to supply and demand variability.

A lean alternative to safety stocks is adoption of multi-supplier configurations to protect manufacturers against uncertainty in supply and demand. These configurations offer diversification benefits such as improved supplier responsiveness [35,36], reduce dependency on single supply sources [18], and increased competition to enhance quality and innovation [37]. Multi-supplier configurations, however, can potentially complicate planning processes [38], storage and movement of purchased goods [39], and inventory accounting [40]. Comprehensive research on cost implications of multi-supplier configurations is sparse and the problem is yet to be formulated in the off-site manufacturing literature [41].

Dynamics of supply-related decisions for off-site manufacturing are discussed in the following section.

2.2. Supply decisions and configurations in advanced manufacturing of prefabricated products

Prefabrication projects are complex and require collaboration of different groups such as precast panel manufacturers and volumetric module producers [42]. Within each group, there are extended supply networks that source required elements and support manufacturing operations [43–45]. In precast panel manufacturing, for example, suppliers provide different elements such as formworks, cast-in plates, ferrules and grout tubes (see Fig. 2).

Reliable supply of required elements is critical to the continuity of workflow in off-site construction and production lines can be shut down due to supply shortfalls. Production disruptions have severe operational and financial consequences for off-site and on-site operations. The problem is of larger scale in make-to-order production settings where available buffers between manufacturing and on-site assembly are small [46]. Considering the criticality of supply decisions in off-site manufacturing, cost is not the sole decision variable. Off-site manufacturers often consider strategic preferences in configuring their supply network [47]. Inclusion of certain suppliers is an example of strategic preference

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