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Optimal logistics planning for modular construction using two-stage stochastic programming

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ABSTRACT

The construction sector is currently undergoing a shift from stick-built construction to modular building systems that take advantage of modern prefabrication techniques. Long established in-situ construction practices are thus being replaced by processes imported from the manufacturing sector, where component fabrication takes place within a factory environment. As a result of this transformation, current construction supply chains, which have focused on the delivery of raw materials to sites, are no longer apt and need to make way to new, strengthened, and time-critical logistics systems. The aim of this study is to establish a mathematical model for the optimisation of logistics processes in modular construction covering three tiers of operation: manufacturing, storage and assembly. Previous studies have indicated that construction site delays constitute the largest cause of schedule deviations. Using the model outlined in this paper we seek to determine how factory manufacturing and inventory management should react to variations in the demand on construction sites. A two-stage stochastic programming model is developed to capture all possible demand variations on site. The model is evaluated using a case study from the residential construction sector. The application shows that the model is effective and can serve as decision support to optimise modular construction logistics.

1. Introduction

Over recent years the practice of modular construction, using the design for manufacturing and assembly (DfMA) method, has progressively entered the construction industry replacing the traditional stick-built approach to construction. The benefits of modular construction come from manufacturing building components in a factory environment, where higher efficiencies and quality can be achieved, the need for space to store materials or equipment on site is reduced, and the assembly process is significantly shortened [4–6].

The structure of the supply chain for traditional stick-built construction projects is usually composed of multiple raw material suppliers that directly deliver to construction sites, with seldom use of consolidation centres for temporary storage [1]. In this paradigm, raw building materials are dispatched to sites on demand, in response to orders placed by the site. Therefore, the configuration of the overall supply chain is straightforward as all the information for decision making such as quantity and timing of materials can be obtained from the construction schedule [2]. In the event of construction schedule deviations, which make the site material demands diminish, deliveries can be temporarily held in supplier warehouses or stored in construction sites until they need to be used [3].

On the contrary, building materials in modular construction projects are rarely sent directly to sites. Instead, most materials are initially transported to the manufacturing facility where they are transformed into modular products and components [4,5]. The modular components leaving a factory are typically large and cumbersome, necessitating extra caution when they are carried across public roads and assembled on site [10]. Furthermore, many construction sites are located in urban settings with limited storage space, which makes warehouses essential for temporary storage [11], thus introducing in the supply chain structure another layer for buffering.

Due to the dependence on complex and unique production processes, and the production of tailor-made and project-specific products, modular construction supply chains are often distinguished from the logistics arrangements encountered in other sectors and are often studied separately [6]. For instance, commonly adopted assumptions such as the ability to procure products at a higher price from other manufacturers, when production fails to meet the demand, may not apply to modular construction. More so, the total quantity of modular products produced in the factory normally matches the demand from the construction sites, and consequently the inventory will reach zero when a

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project ends. This phenomenon is in contrast to the supply chains of ordinary retail products, where inventory needs to be preserved as safety stock. Furthermore, unlike ordinary retail products, additional assembly processes and costs are required after the products are delivered to the site.

Satisfying the demands on modular construction sites is often challenging as various delay factors can introduce uncertainty. The construction industry regards delays in construction schedules to be inevitable [7] and directly linked to additional costs [8]. Their causes can generally be traced to factors internal to construction sites such as human errors and equipment failures [9] as much as external factors such as extreme weather conditions. Previous studies have focused on the mitigation of construction delays in stick-built projects through supply chain interventions [3]. However, the adoption of modular construction practices introduces an additional layer of complexity, given the interplay of manufacturing, transportation and assembly (MtA) processes.

The optimal configuration for a three-tier modular construction supply chain including a manufacturing factory, a storage facility, and construction sites has not been studied before. Previous research on the supply chains of stick-built construction as well as general merchandise can only partially inform a new logistic model for modular construction as the aforementioned features require additional considerations.

This research aims at addressing this knowledge gap by establishing a mathematical model to optimise logistics processes in modular construction. The model proposed in this study, accounting for stochastic demands on site, is capable of identifying the optimal factory production plan and transportation scheme, and revealing the change of inventory in the factory, warehouse and site for multiple time horizons. The outputs of the model can be of great value to managers responsible of either issuing plans to be executed in the future or making changes to existing plans to account for recently revealed data.

The rest of the paper is structured as follows. Section 2 reviews work on supply chain integration, the origins of demands uncertainty in modular construction and stochastic supply chain network design. Section 3 introduces the methodology including assumptions and model formulation and objective function. Section 4 covers model implementation, case study and discussion. Section 5 draws the conclusions.

2. Background

In this section, we provide an overview of current research in supply chain integration under demand fluctuation in both the manufacturing and construction industry. Methods for the design of optimal supply chain configurations under uncertain demands are also reviewed.

2.1. Supply chain integration

Supply chains are commonly modelled as dynamic systems involving multiple interacting parties. Careful coordination is considered essential across the organisational boundaries to create a seamless and value-added process for fulfilling all customer needs [12].

Chandra and Fisher [13] pointed out that in supply chain design, the activities in different echelons should be considered simultaneously to achieve high overall efficiency. Coelho and Laporte [14] suggested that decisions in production planning, shipment scheduling and inventory management should be modelled in a single problem statement. In this context, a model and its optimal solution can serve as the foundation for tactical decision making in complex supply chain design [15].

Supply chains integrating multiple stakeholders have been previously explored and modelled. Lei et al. [16], for example, developed a model which considered production, inventory, and distribution synchronously. In their study, the most appropriate operation schedule needed to satisfy constraints including customer demand, vehicle capacity, and production limits.

A recent review by Díaz-Madroñero et al. [19], summarising research trends in supply chain integration studies, found that a commonly adopted requirement is the absolute satisfaction of customer demands. However, in a supply chain, customers, distributors, and suppliers typically have different and occasionally conflicting objectives. For instance, customers are predominantly concerned with their demand being fulfilled on time, while distributors aim at dispatching all the goods within minimum vehicle run, and suppliers focus on producing products at the lowest cost with demand fulfilment as a secondary goal. To address them concurrently stakeholders' objectives should be jointly considered and linked together. In this context, a network-based analysis is, therefore, well-placed to determine the freight transport configuration that maximises the profit of every stakeholder [17]. Elimam and Dodin [18] combined the production and distribution chains into one integrated supply chain (ISC), which includes all the stakeholders over multiple echelons. The ISC is represented as a project network with different types of activities, thus capturing all the flow of information and goods within the supply chain.

In the studies reviewed above, mixed integer linear programming (MILP) is the most commonly used modelling framework for supply chain design problems, with solutions typically obtained by a mix of exact algorithms, meta-heuristics and decomposition techniques [19,56,61].

2.2. Origins of demand uncertainty in modular construction

It is common practice in modern construction that the specific material demand and delivery plans are prepared during the design stage. When construction starts, there are many factors that will ultimately lead to deviations from the originally planned schedules. Gündüz et al. [9] listed 83 distinct factors causing delays in building projects with over 90% traceable to activities within construction sites. When delays occur, the actual progress of the project lags behind the original schedules. Material demands will, therefore, decrease, and project duration will have to be extended, incurring additional costs [8]. Since delays in construction schedules are almost inevitable [7], and changes in the demand often have a severe impact on the upstream logistics, their effect must be carefully taken into consideration [20,62].

Zou et al. [21] proposed a technique for predicting the demand uncertainties on the construction site by using a probabilistic analysis on historical data. Generally speaking, the demand variation of construction material can often be conceived in a stochastic form [22–24], which is established by combing various reasons for causing schedule deviations with their severity toward the original demand. Illustrating these demand uncertainties in a mathematical model and identifying the optimal solution, which can effectively mitigate the extra cost incurred are problems that have to be addressed when building a logistic system for modular construction.

2.3. Stochastic supply chain network design

Various methods have been proposed to deal with uncertainties in supply chain design, such as stochastic programming, fuzzy set theory, robust optimisation and dynamic stochastic programming [25]. Among them, the two-stage stochastic programming has been commonly adopted, because it can capture different types of uncertainties, which may occur in the supply chain [26]. Moreover, it can output the optimal supply chain configuration in terms of production planning, inventory management, capacity planning and routing [27]. Ierapetritou and Pistikopoulos [28] sought the optimal production lot quantities when customers' demands are uncertain. The problem was modelled by two-stage stochastic programming with an objective function for minimising the total operational cost and the expected penalty cost incurred by the unmet customer demand.

Tsiakis et al. [29] and MirHassani et al. [30] implemented a two-stage stochastic programming model to find out the optimal network