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

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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

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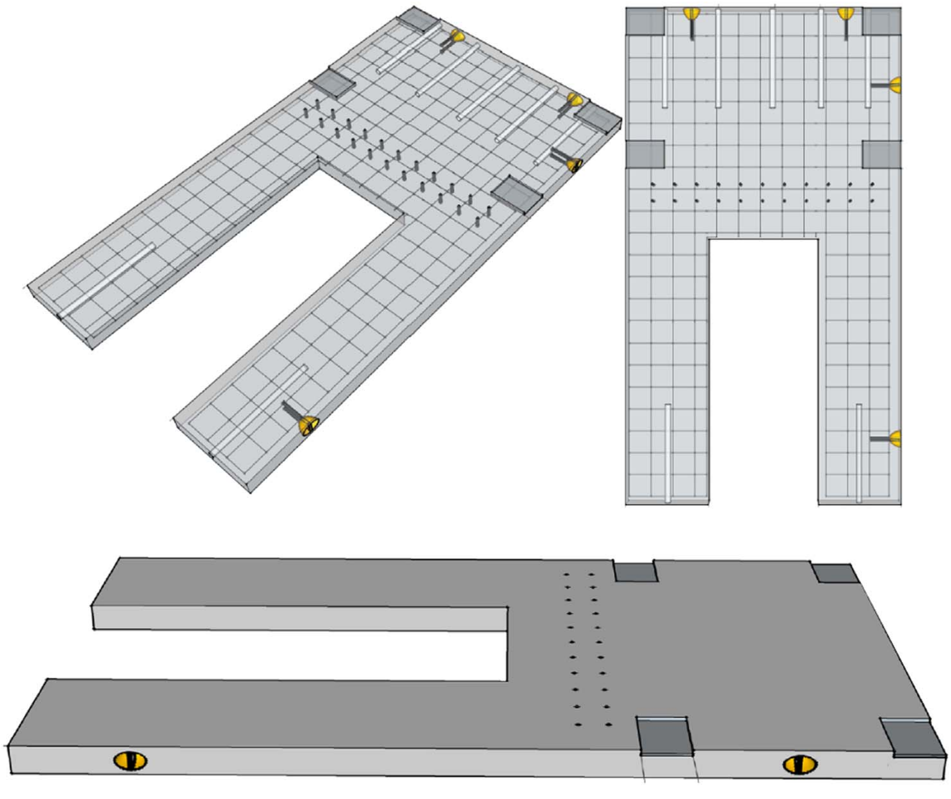

Fig. 1. Prefabricated wall panels and embedded elements.

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

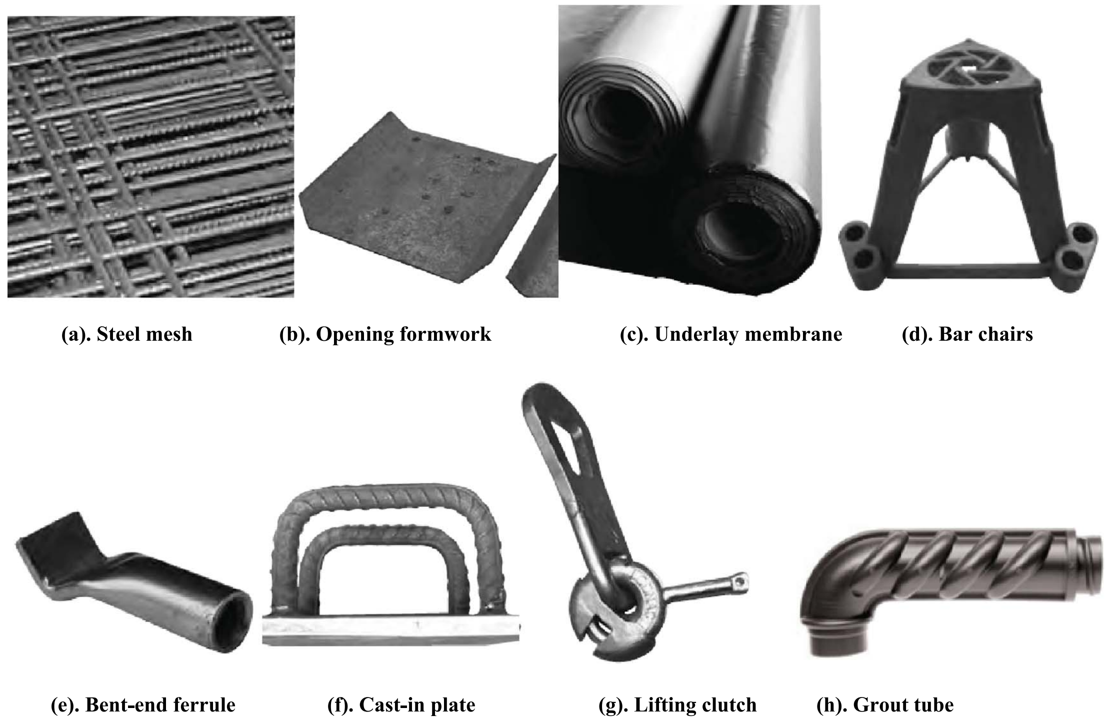

Fig. 2. Examples of required elements in precast panel manufacturing.

in supply decision making. Previous research highlights the reasons behind this preference such as sustained business relationships and the need for code compliance [48]. A second purchasing preference is to exclude suppliers due to a history of delays and incompatibility of their products [49]. Furthermore, inclusion of some suppliers can result in exclusion of others because of overlapping portfolio of supplied products and business relation considerations [50]. A variety of operational research methods such as linear programming have been utilized to model supply-related decisions under the influence of strategic preferences [32,43]. However, to the authors' best knowledge, cost implications of such preferences for off-site manufacturing have not been analyzed.

The modeling framework adopted in this research and development process of three research hypotheses are discussed in the following section.

3. Research method

3.1. Modeling framework

The modeling practice in this research is based on the following fundamental assumptions:

- Advanced manufacturing of building products is not a self-contained practice and collaboration with supply networks is always required. Complexity and comprehensiveness of supply networks in off-site manufacturing justify this assumption.
- Availability of required elements is a key variable in determining the production service level. Consequently, each and every element needs to be sources by at least one supplier.
- Strategic preferences can be specified by manufacturers to include/exclude a group of suppliers. These preferences can be based on a range of reasons such as technical grounds, standard compliance, and business relationships.
- Decision making on suppliers in off-site construction is subject to uncertainty and resultant risk of deviations from targeted plans. Departure from a single-supplier configuration to multiple-supplier is a possible approach in addressing the present uncertainty.

3.2. Hypothesis development

Total supply cost in construction production networks is inflated as a result of suboptimal purchasing decisions [51], variability in shop floor production rates [52,53], and uncertainty in supply processes [54,55]. Safety stocks or contingency inventories are commonly used to increase the service level of manufacturing networks [56]. However, inventory buffers in dynamic production environments are wasteful and difficult to optimize in terms of size [34]. An alternative approach to enhance the overall performance of networks and minimize relative costs is to optimize supply configurations [31,57]. Standard modeling methods such as linear programming have been used in the manufacturing literature to optimize supply decisions [58,59]. However, such optimization models have not been customized to reflect unique characteristics of production in off-site construction for example the complexity and comprehensiveness of supply decisions in comparison to traditional construction [60].

Within the complex supply chain of prefabricated construction, it remains a nontrivial task to minimize the total supply cost and the effectiveness of modeling techniques such as linear programming needs to be tested. This leads to development of the first hypothesis in this research,

Hypothesis 1. : Supply configurations in multi-product multi-supplier prefabrication can be optimized using zero-one linear mathematical programming.

One of the main objectives of optimizing the supply chain configuration in off-site construction is to minimize the overall supply cost. However, selection of suppliers and network configuration is not solely based on lowest supply fees. In real production scenarios in off-site construction, different logical constraints are often considered in the decision making process [61]. These logical constraints can represent strategic preferences of the manufacturer to include or exclude certain suppliers in sourcing required elements [62]. Furthermore, such preferences can specify the nature of relationships within the supply network where for example, inclusion of some suppliers results in exclusion of others due to compatibility of products or business relationships [63,64]. Understandably, addition of strategic preferences will result in a tighter configuration of the supply network. However, dynamics around cost implications of such preferences are not fully understood and need further investigation [25]. Consequently, the second hypothesis of the paper is advanced as,

Hypothesis 2. : Cost of supply decisions in advanced manufacturing of prefabricated products is not significantly impacted by imposing purchasing strategic preferences.

Optimization of supply chain management decisions and configurations can improve tangible performance measures and minimize supply disruption risks [21]. As an example, departure from a single supplier model to multiple suppliers for some/all required elements addresses the supplier reliability issues and reduces disruption risks [65]. Previous research has shown positive impacts of multiple supplier models on reducing lead times [66], lower order times [32], and improving supply reliability [18]. However, the question then arises whether or not addressing the supply uncertainty by adopting multiple supplier models decreases the total supply cost. This leads to the development of the final hypothesis in this research,

Hypothesis 3. : Minimizing disruption risks by adopting multi-supplier configurations reduces the total supply cost in the advanced manufacturing of prefabricated products.

The modeling framework used to test the aforementioned hypotheses has been illustrated in Fig.3.

4. Optimization of supply decisions in advanced manufacturing of prefabricated components

4.1. Base model

The supply optimization model in prefabricated construction can be formulated using the following notational definitions,

${x_{s_j}}^{e_i}$ Decision variable indicating if supplier s_j is the optimal source for element e_i

$(x_{sj}^{e_i} \in \{0, 1\})$

${\varphi_{s_j}}^{e_i}$ Supply match where element e_i can be sources by supplier s_j

$(\varphi_{sj}^{e_i} \in \{0, 1\})$

${\delta_{s_j}}^{e_i}$ Supply cost of element e_i by supplier s_j

$(\delta_{sj}^{e_i} \geq 0)$

λ Minimum number of required elements to be sourced by multiple suppliers

$0 \leq \lambda \leq 1$, *integer*

ξ_{e_i} Variable controlling the number of suppliers (decision making under uncertainty)

$(\xi_{e_i} \in \{0, 1\})$

The objective of the optimization model is to minimize the total supply cost in off-site construction. Model constraints will enforce the coverage of all required elements by at least one supplier. The base model for supply optimization representing the goal function and set of constraints is formalized in Eq. (1), where Z is the total cost of supply for a given production scenario. Note that the decision variable ${x_{s_j}}^{e_i}$ only becomes one when its associated element e_i is sourced by a supplier s_j within the supply network.

$$\text{Minimize} \quad Z = \sum_s x_{sj}^{e_i} \times \delta_{sj}^{e_i} \tag{1}$$

subject to:

$$\sum_s x_{sj}^{e_1} \times \varphi_{sj}^{e_1} \geq 1 \qquad \forall\, e$$

$$\sum_s x_{sj}^{e_2} \times \varphi_{sj}^{e_2} \geq 1 \qquad \forall\, e \qquad \textit{Shopfloor constraints}$$

$$\ldots$$

$$\sum_s x_{sj}^{e_i} \times \varphi_{sj}^{e_i} \geq 1 \qquad \forall\, e$$

$$x_{sj}^{e_i} \in \{0, 1\} \qquad \textit{Binary constraint}$$

4.2. Optimization of supply chain decisions with strategic preferences

The base model represented by Eq. (1) ensures that each and every required element is sourced while maintaining the lowest supply cost. That is, only suppliers that can satisfy the aforementioned criteria are included in the supply chain configuration. Strategic preferences, however, can encourage inclusion of certain suppliers in prefabrication of building elements. A logical constraint (Eq. (2)) can be added to the base model to enforce inclusion of single or set of supplier(s),

$$\sum_s x_{s_k} \geq k \qquad k \leq j \tag{2}$$

The value of decision variable x_{s_k}becomes one if the supplier s_k is selected. Similarly, if the strategic preference is to include 5 suppliers then $\sum_s x_{s_k} \geq 5$. It should be noted that Eq. (2) is an additional constraint to the existing logic of the base model (Eq. (1)). Understandably, the additional constraint can become binding and control the optimal modeling solution when large values for parameter k are desired.

A second strategic preference is the exclusion of some suppliers from network configuration if certain suppliers are selected. Common justifications for this preference are product compatibility and overlapping supply capacity for similar sets of products [67,68]. An exclusion constraint (Eq. [3]) is added to the base model to enforce this strategic preference,

$$\sum_s x_{s_n} \leq n\,(1 - \sum_s x_{s_m}) \qquad n \leq j - m \tag{3}$$

As can be seen, Eq. (3) turns the base model to a set covering problem where selection of set m of suppliers result in exclusion of set n. In other production scenarios, inclusion of some suppliers in the network configuration encourages involvement of certain suppliers. This can be due to synchronized delivery advantages and geographical proximity, or existing business relationships within the supply network [69,70]. This strategic preference can be enforced by adding Eq. (4) as a new constraint to the base model,

$$\sum_s x_{s_a} + \sum_s x_{s_b} \geq \sum_s x_{s_c}\Big) \qquad a + b + c \leq j \tag{4}$$

By applying this logical constraint, selection of supplier set c, results in automatic selection of sets a and b as well.

4.3. Optimization of supply decisions under uncertainty

Decision making on supply configurations is subject to uncertainty in relation to supplier reliability [26]. This uncertainty and resultant risk of supply disruptions can be addressed by adopting a multiple supplier instead of single supplier configuration [20,71]. Utilizing a multi supplier constraint, the optimization model for supply decisions under uncertainty is formulated using Eq. (5) where ξ_{e_i} is a binary variable associated with each and every required element (e_i).The variable only becomes one when e_i is sourced by more than one supplier. Note that the expression of $\sum_s x_{sj}^{e_i} \times \varphi_{sj}^{e_i}$ specifies how many times element e_i is covered and will be at least two if $\xi_{e_i} = 1$. The minimum

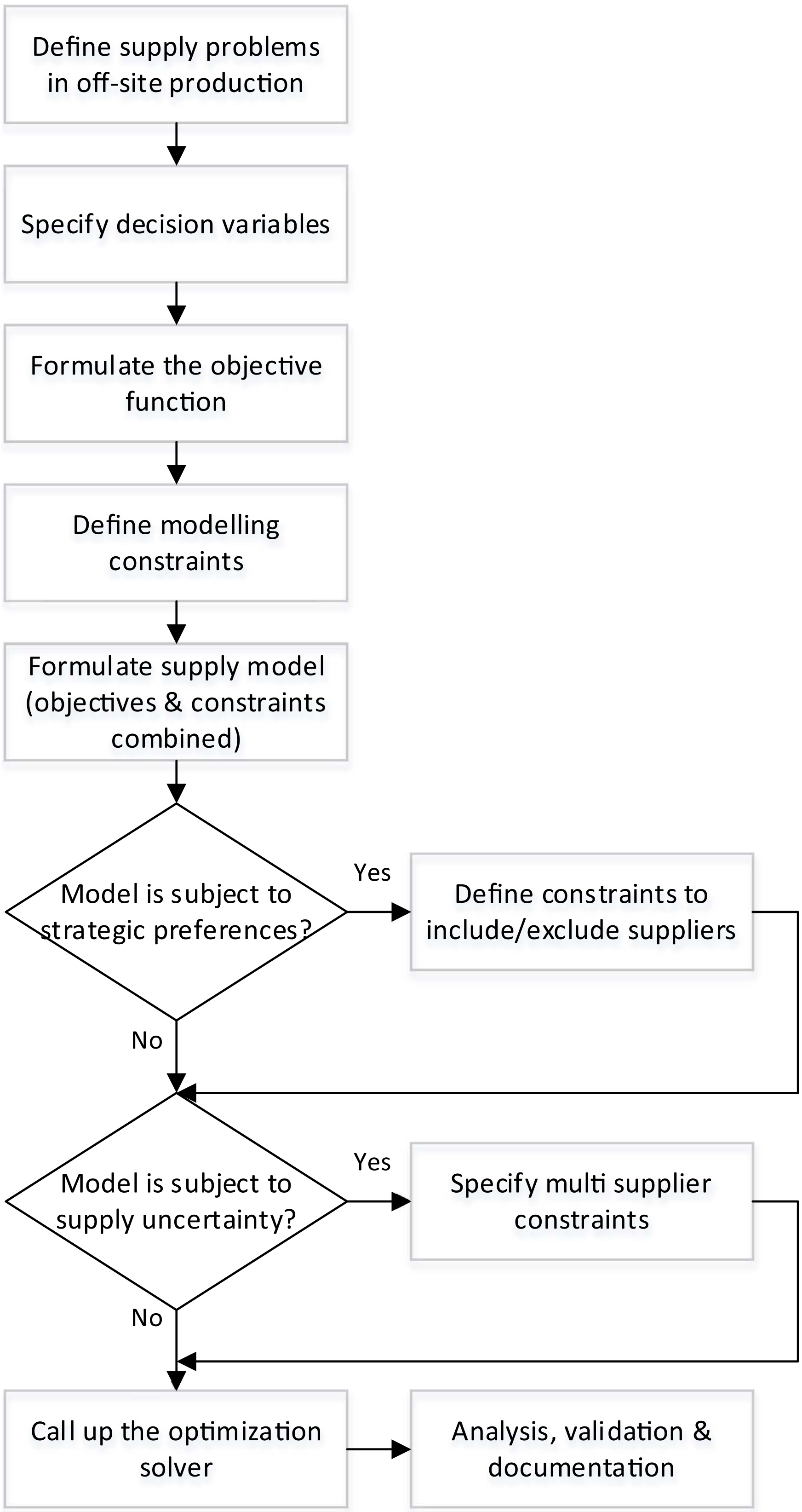

Fig. 3. Modeling methodology.

number of required elements that should be sourced by multiple suppliers is denoted by λ.

$$\text{Minimize} \quad Z = \sum_{s} x_{sj}^{e_i} \times \delta_{sj}^{e_i} \tag{5}$$

subject to:

$$\sum_{s} x_{sj}^{e_i} \times \varphi_{sj}^{e_i} \geq 2\xi_{e_i} \qquad \forall\, e \qquad \textit{Multi supplier constraint}$$

Table 1
Suppliers of required elements in off-site manufacturing of precast concrete panels.

Elements/suppliers	A	B	C	D	E	F	G	H	I
E1: steel mesh				1		1	1	1	
E2: inner formwork for openings		1	1				1		1
E3: underlay membrane		1			1	1			
E4: clips & bar chairs			1		1				1
E5: ferrules & accessories	1						1	1	
E6: cast-in plates			1	1		1			
E7: fillets & mock joints					1	1			1
E8: dowels & connections		1		1				1	
E9: bracing inserts		1			1				1
E10: lifting inserts & clutches	1		1				1		
E11: grout tubes	1			1				1	
Supply cost	$49,800	$55,000	$76,500	$79,600	$68,900	$73,700	$78,300	$79,200	$71,000

$$\sum_{e} \xi_{e_i} \geq \lambda \qquad \lambda \leq j$$

$$\xi_{e_i} \in \{0, 1\} \qquad \textit{Binary constraint}$$

Computational results yielded by running models are presented in the following section.

5. Modeling validation and results

The developed models are validated and their computational efficiency is tested using real production data of a precast panel manufacturer. Information about quantity of required elements, respective costs and capacity of suppliers were fed into the developed models. Table 1 presents an extract of data on 11 required elements sourced by nine different suppliers (A to I). Supplying sources have been codified and names are not disclosed due to privacy considerations. As can be seen in Table 1, supplier H, for example, is capable of sourcing steel mesh, ferrules and accessories, dowels and connections, and grout tubes.

The first null hypothesis of this research (H1) proposes that supply chain configurations in advanced manufacturing of prefabricated elements can be optimized using zero-one linear mathematical programming. In order to test H1, values of $\delta_{s_j}^{e_i}$ and $\varphi_{s_j}^{e_i}$ $(i = 1, \ldots, 11; j = 1, \ldots, 9)$ were fed into the developed linear model (Eq. (1)) to compute the decision variable $x_{s_j}^{e_i}$. The proposed optimization model is based on programming strategy underlying the binary (zero-one) approach. Running the optimization model yields a total supply cost of $224,600. Although relaxation of the binary constraint in Eq. (1) and solving a linear variation of the base model yields lower supply cost of $201,167, this result is unrealistic as fractional solutions for the decision variable $x_{s_j}^{e_i}$ are not feasible. Consequently H1 is supported as the zero-one programming approach can optimize the supply decision making on multi-product multi-supplier scenarios.

In order to test hypotheses H2 and H3, logical constraints were added to the base model using the pseudo code presented in Fig. 4.

The second null hypothesis (H2) proposes that imposing purchasing strategic preferences on the process of supply decision making does not have significant cost implications. Logical constraints representing strategic preferences (Eq. (2) to Eq. (4)) are added to the base model and total supply costs for different production scenarios computed.

Running the constrained optimization model including the inclusion constraint yields a total supply cost of $276,600, showing an increase of 37.49% compared to the base case. More importantly, combining several strategic preferences result in a total supply cost of $325,700 with 61.91% increase compared to the base case (see Table 2). Optimization results lead to rejection of H2 and confirm that introduction of strategic preferences in purchasing to supply decision making has significant cost implications.

Optimization models (base case and strategic preference models) were run using a laptop with the following specifications. The processor is Intel Core i5–6500 CPU (3.20 GHz), installed RAM memory is 8.0 GB, and system type is 64-bit operating system (× 64-based processor). The computing time to find optimal solutions to the base case and the model with combined strategic preferences are 16.73 and 21.40 s respectively. The addition of logical constraints representing strategic preferences resulted in 28% increase in computational times.

The third null hypothesis (H3) proposes that adopting a multi supplier model configuration in order to minimize supply disruption risks will result in decreasing total supply costs. In order to test H3, values of $\delta_{s_j}^{e_i}$, $\varphi_{s_j}^{e_i}$, ξ_{e_i} and λ were fed into Eq. (5) to compute the decision variable $x_{s_j}^{e_i}$ under uncertainty. Eleven production experiments are tested by varying the minimum number of required elements to be sourced by multiple suppliers ($\lambda = 1, \ldots, 11$). Running optimization models for different production scenarios yields different total costs for supply as illustrated in Fig. 5.

As can be seen in Fig. 5, introduction of multi-supplier configuration to more products results in progressive increase in supply decision costs. As an example, sourcing five products by at least two suppliers yield a total cost of $279,600, showing an increase of 38.90%when compared to the single-supplier strategy. The rejection on H3 based on above results is in line with findings of Lam, et al. [72] and Azambuja and O'Brien [73] confirming that departure from single-supplier to multi-supplier configurations in multi-product settings increases the total cost of supply.

6. Limitations

Optimizing supply decisions and configuration parameters is a complex analytical problem. The decision-making system that is provided in the paper does not consider the temporal dimension explicitly. In real-life production scenarios, however, supply contracts are signed for a fixed duration, and these may vary by supplier and by product. Furthermore, the analysis in the current research is limited to available production data on 11 types of supplied elements and nine different suppliers.

There are numerous strategic preferences for purchasing in real-world manufacturing of prefabricated products. The modeling framework in this research only considered some preferences with regard to supplier inclusion, exclusion and relationships within the supply network. Finally, supply disruption risks can be minimized using a wide range of strategies. Multi-supplier configuration was the selected risk minimization process in the current research.

7. Conclusions

The optimization of supply decisions and configuration parameters has long attracted researchers in the manufacturing domain [74–76]. However, related research in the off-site construction domain, which is a hybrid of manufacturing and construction, is sparse [77,78]. In order to bridge this gap, the current research modeled several supply

```
VariablesMIP   := data ( IsSelectedMIP, TotalCostMIP );
ConstraintsMIP := data ( TotalCostMIP, ElementsAreSuppliedMIP );

if (LogicalConstraintsIsSelected('Must include suppliers A & G')) then
      ConstraintsMIP += 'MustIncludeAandG';
endif;

if (LogicalConstraintsIsSelected('If Suppliers D or E')) then
      ConstraintsMIP += ( 'IfSupplierD','IfSupplierE');
endif;

if (LogicalConstraintsIsSelected('If supplier E, then no C, D and H')) then
      ConstraintsMIP += ( 'IfSupplierEthenNoCandDandH' );
endif;

if (LogicalConstraintsIsSelected('Minimize risk of supply disruptions')) then
      ConstraintsMIP += ( 'MoreThanOneSupplier', 'nElements' );
      VariablesMIP += ( 'SupplyElementsByMoreThanOneSupplier' );
endif;
```

Fig. 4. Pseudo code for introducing logical constraints to the base model.

Table 2
Cost of supply decisions under influence of strategic preferences in purchasing.

Supply decision	Respective cost of decision	Cost increase compared to the base model
Linear programming	$201,167	–
Zero-one programming	$224,600	11.65%
Force supplier exclusion	$247,400	22.98%
Force supplier inclusion	$276,600	37.49%
Supplier relation constraint	$247,400	22.98%
Combined constraints	$325,700	61.91%

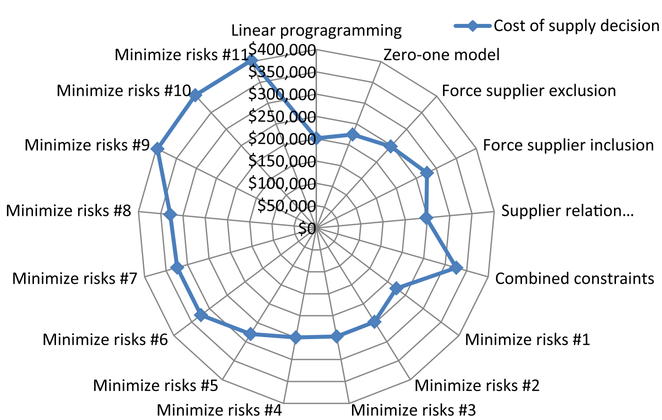

Fig. 5. Associate cost of supply configurations.

configurations with the aim of optimizing supply performance with smaller levels of investment. The modeling procedure shows effectiveness of standard operational research approaches such as zero-one (binary) mathematical programming in analyzing supply decisions. Furthermore, mathematical models lend themselves to accommodate strategic preferences for purchasing in off-site manufacturing of prefabricated products.

The research results confirm that minimizing disruption risks with the aid of multi-supplier configurations in multi-product settings leads to inflation of the total supply cost. Tradeoffs need to be made in using such configurations to balance costs and benefits of risk mitigation. That is, utilization of multi-supplier configurations should be limited to critical purchase elements whose shortages result in major process disruptions for the off-site manufacturing processes.

The current research contributes to the supply chain theory in construction by formulating decision parameters that are commonly perceived difficult in quantitative analytical modeling. Theses parameters include strategic purchasing preferences and risk mitigation strategies in decision making under uncertainty such as departure from single-supplier to multi-supplier configurations. The paper contributes to the prefabricated manufacturing practice by streamlining supply decisions under several logical constraints.

Future research can expand the developed models using larger datasets for supplied products and also vendors. Furthermore, additional strategic preferences and risk mitigation approaches should be incorporated into multi-supplier production scenarios.

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