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Decision model for planning material supply channels in construction

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ABSTRACT

Material supply-related decisions strongly affect economic performance of construction projects. To facilitate planning, the authors put forward a mixed integer linear programming model for optimizing supplies of materials or components that are consumed irregularly. The model's objective function is minimizing the total inventory management cost. As material prices change over time and cannot be predicted with certainty, they are expressed as fuzzy values with triangular membership functions. The planning horizon is divided into units of time to allow for seasonal changes and scope variations that affect consumption of materials. The model enables the user to determine economic order quantities for consecutive periods of construction works and to select most economical supply channels of a particular material/component. The model allows for material/component substitution. Substitutes may differ in level of prefabrication and thus in costs of on-site processing. To solve the problem the fuzzy model is converted into a three-objective linear program with crisp coefficients. An example illustrates benefits of using the proposed approach in reducing the total inventory cost.

1. Introduction

The researchers and practitioners keep arguing over specific features of construction supply chains compared with the supply system in the production environment [1–3], and trying to elicit guidelines for their efficient management. These guidelines draw upon experience of the manufacturing industry [4,5] or, on the contrary, build upon the assumption of independent and rational evolution of each industry, with management ideas not being directly transferable between them [6–8].

Among construction supply chain activities, material/component procurement is one of the most demanding tasks [9]. Materials are consumed in large quantities and, obviously, need to be delivered to a “random” location (selected where the built facility is required, not where materials are available or easily transportable). The share of material-related costs, though project-, and country-specific, may be as high as 40 to 70% of the total hard cost of construction [10–12]. Therefore, the search for economies often focuses on managing materials in most effective way [13]. Efficient material logistics is considered a key determinant of project success. This is especially true in construction, with its tough competition, adversarial relationships, and traditionally low profit margins [9,14,15].

Mathematical models constructed to facilitate supply decisions are expected to allow for the real-life complexity and dynamics. Therefore, the authors put forward an Economic Order Quantity model (with its origins in manufacturing industry [16]) to minimize total inventory management cost. Though the method is classic (linear programming), the model's originality lies in adopting a unique set of constraints deemed typical for construction projects. To account for erratic material price fluctuations observed recently – so uncertainty of prices – the authors use fuzzy logic, and analyze a number of scenarios of future price development.

The purpose of the model is to facilitate finding a rational supply plan for construction materials or components that are consumed in large quantities, irregularly (according to the schedule of works), and for a time long enough to prevent the suppliers from guaranteeing fixed prices.

The model is meant to account for constraints related with the source's production capacity and availability of means of transport. This implies modelling effects of intermediate storing or contracting a number of suppliers to provide the same type of material. As opportunity purchases at lower prices may be justified, storage facilities need to be arranged and encompassed by the model.

Another assumption is that the model is to allow for material substitution. Substitution, understood as replacing one type of material or component with another with no detriment to quality or function of the final product, may be a result of material shortages or searching for economies (including make or buy decisions). The benefits of substitution are referred to in the literature, such as increasing flexibility of agile supply networks operating in competitive markets [17]. Enabling

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the contractor to propose alternative technical solutions that can equally perform the required functions of the specified items is encouraged by public procurement legislation (e.g. EU Directive on Public Procurement, 2014/24/EU article 74, US Federal Acquisition Regulation 11.104) to avoid favoritism and corruption and promote innovation. Substitution may be also welcome due to sustainability reasons [18–20].

The remainder of the paper is organized as follows: Section 2 reviews literature related to supplier selection problem. Section 3 defines the problem and proposes its mixed integer linear formulation. Section 4 presents details on the model formulation. Section 5 discusses the results by providing an illustrative example: application of the model to finding optimal set of suppliers in consecutive stages of a notional project. Concluding section summarizes findings and puts forward directions for future research.

2. Literature review

One of the distinctive features of construction material supply system is the fact that the chain is formed per project by the initiative of the contractor. The contractor reviews possible material sources and selects most suitable vendors. As the industry keeps being focused on the efficiency of individual projects and relies upon competitive tendering procedures [21,22], the set of supplier assessment criteria usually involves price and other delivery conditions promised in relation to a particular project, as well as criteria related to qualities of the supplier (performance history). The lists of criteria for supplier selection proposed in the literature were usually compiled on the basis of expert opinions collected in interviews. These proved surprisingly consistent [23–25], though relative importance of criteria differed according to location-specific economic constraints at the time of survey.

With the criteria agreed, the next problem is finding a suitable method of multi-criteria analysis. Many attempts to model construction supplier selection problems consisted in multi-criteria ranking of the suppliers for a one-off transaction. Among others, Lam et al. [25] argued for applicability of fuzzy principal component analysis as it helped avoid multicollinearity among the criteria and eliminate the errors of subjective weighting. Aretoulis et al. [26] used a form of simple additive weighting model to provide numerical scores for each assessed supplier; they provided it together with a method for criteria selection and weighting. Safa et al. [22], in their integrated model for construction materials management, decided to assess suppliers by means of TOPSIS for its computational simplicity, long tradition of use in construction-related decision making, and applicability in the analysis of both qualitative and quantitative criteria. Plebankiewicz and Kubek [27] argued that Analytic Hierarchy Process and its fuzzy extension better correspond to subjective nature of criteria assessment. Polat and Eray [28], having used AHP to weight assessment criteria for the same reason, ranked the suppliers by means of evidential reasoning technique.

However, a decision model based on the assumption of one-off purchase is not enough. It should allow for the fact that some construction materials are to be supplied during the whole duration of the project, that the demand may vary over time due to project-specific schedules, and that prices may fluctuate. If materials are required in large quantities over some time, the problem of changing supplier capacities may be worth considering together with a possibility of using substitutes or delivering the same material from more than one source at a time. Many models that allow for all or some of these aspects were presented in the literature [29–33].

A mixed integer non-linear formulation of dynamic supplier selection problem can be found, among others, in [29], where the authors minimize total cost of providing multiple parts from multiple suppliers in multiple periods. The total cost comprises unit price of purchasing the part from supplier, cost of delays beyond the lead time, cost of rejecting a batch due to inadequate quality, and the cost of transportation. These are specific to each supplier.

Ghodyspour and O'Brien [30] studied multiple sourcing problem with multiple criteria and capacitated suppliers, developing a mixed integer non-linear programming model to find the least-cost cyclic ordering policy for the buyer. Chern and Hsieh [31] compared several multi-objective optimization methods of vendor selection for an outsourcing problem analogous to the problem of on- or off-site pre-processing in construction, though they analyzed complex supply networks and focused on quantity discounts. In search for solutions, the authors use heuristic algorithms and compare a number of multi-objective programming approaches.

The possibility to substitute considerably increases the number of potential supply channels and makes the decision-making process more complex. With a large number of variables to be considered, Luo et al. [32] claim that artificial neural networks were a particularly useful tool to quickly revise many optional suppliers to rank them or to pick their best combinations.

As mentioned in the Introduction, another issue specific to construction projects is changing demand for material types and quantities over the planning horizon. An interesting contribution to construction-dedicated supply planning and optimization that answers to this problem can be found in [33]. The author analyzed the problem of selecting suppliers of bulk materials to serve multiple projects – with the assumption of full-load customer demand, with restricted delivery time windows, together with assigning vehicle types to deliveries, and sequencing the materials pickup and delivery operations to meet all the delivery requirements on time at minimum total sourcing and delivery cost. The main purpose of the model is to support tactical planning of procurement and vehicle deployment within the planning horizon. The problem was formulated as an integer programming model, and the solving procedure is based on a linear programming-based heuristic.

Construction is generally considered prone to many risks. This should be reflected in planning supplies. Therefore, some authors treat their input as random variables and use simulations or stochastic programming to construct supplier selection models (e.g. [34–37]. Fuzzy logic has been widely applied to model uncertainty in supply management problems. Kao and Hsu [38] sized deliveries on the basis of fuzzy demand in Economic Order Quantity model, but they based on fixed unit costs. Kumar et al. [39] challenged deterministic modelling by applying fuzzy goal programming to the problem of supplier selection in manufacturing sector; this approach would be suitable also for construction. Giannoccaro et al. [40] used fuzzy set theory in modelling uncertainty of demand and inventory cost for the problem of inventory control within supply chain. Carlsson and Fuller [41] proposed a fuzzy approach to reduce the bullwhip effect in the supply chain. Petrovic et al. [42] expressed uncertain customer demand and delivery size as fuzzy sets in their model of supply chain to find order quantities that assure required service levels at reasonable cost, and analyzed behavior of the supply chain by means of simulation [42–44]. Więcek [45] experimented with combination of fuzzy logic and genetic algorithms to better model demand and lead time risk.

Works listed above are a small fraction of the rich literature on the subject, presenting a broad scope of models differing in the level of complexity and modelling methods. The approach presented in this paper is inspired by their findings and the analysis of the typical supplier selection practices observed in Polish construction market. The proposed approach allows for non-uniform demand for a material, a possibility to deliver the same material from a number of sources, partial substitution of the material, and a possibility to keep stocks outside the construction site. The objective function of the proposed mixed integer linear programming model is minimizing the total inventory management cost. To allow for uncertainty of material prices, the authors expressed the estimates as fuzzy sets. This was due to difficulty in using purely statistical methods that rely on price records. In the authors' opinion, fluctuations of construction material prices, though carefully observed and recorded by both national statistical

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