SELECTING MATERIAL SUPPLY CHANNELS FOR CONSTRUCTION PROJECTS: A DECISION MODEL

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Abstract

The purpose of research is to analyse and model the construction project's material supply to support logistic decisions. Materials management and delivery planning decisions have a considerable impact on economic outcomes of projects: they condition the flow of works and strongly affect cost. With regard to cost, the factors to be considered are not only the delivery quantities and time, but also selection of suppliers, places of depot, or the level of pre-processing, prefabrication or assembly prior to delivery. To allow for specific conditions of construction operations, the problem was approached by defining the decision problem, constructing the model and finally applying the model to find solutions of a notional case. The proposed model is a mixed integer linear programming model for optimizing supplies with materials consumed irregularly, enabling the user to determine economic order quantities for consecutive periods of construction works and to choose from available supply channels of a particular material/component or its substitutes, if applicable. The model enables the user to minimize total inventory management cost including costs of on-site pre-processing. It can be the basis of decision support tools. Though the paper presents a construction-customized model of supplies with only one type of material, it can be easily adapted to planning any other materials or components that require pre-processing prior to their application, with this pre-processing possible to be conducted on- or off-site.

Key words

Construction; decision model; dynamic supplier selection problem; mixed integer linear programming; supply chains.

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1 INTRODUCTION

With tough competition on the market, the client's high expectation towards time, cost and quality of services, and growing technical complexity of construction projects, efficient logistics becomes a key determinant of success in construction [1]. Typically, materials and materials handling have a most significant share in the total cost of construction (up to 70%), so the search for economies naturally focuses on managing them in most effective way [2, 3]. Therefore, supplies management is conducted in each stage of project lifecycle – from definition of strategic aims to planning operations on-site (Figure 1).

Fig. 1: The idea of decision support in construction management logistics

Selection of the best possible supply channels is a difficult though rewarding task. Using the shortest supply chains with the project being supplied directly from the source seems justified as it theoretically reduces non-value adding handling and excludes intermediaries (Figure 2a), but it is not always possible and economical. As the construction site is a temporary organisation, it is not always reasonable to equip it with all necessary facilities, and the "make or buy" problem needs to be solved: some materials may be pre-processed off-site into components, thus reducing the effort and time of on-site activities (Figure 2b). Many construction materials are bulk materials – consumed in large quantities, relatively cheap but of high transportation cost, and their supply is subject to constraints related with the source's capacity and availability of means of transport. Due to this fact, intermediate storing (Fig. 2c), contracting a number of suppliers to provide the same type of material, or involvement of intermediaries such as forwarding companies, may become inevitable. As construction projects take time and economic circumstances change, the suppliers may be unable to guarantee fixed prices. Opportunity purchases at lower prices may be justified in advance of the works – so storage facilities need to be arranged.

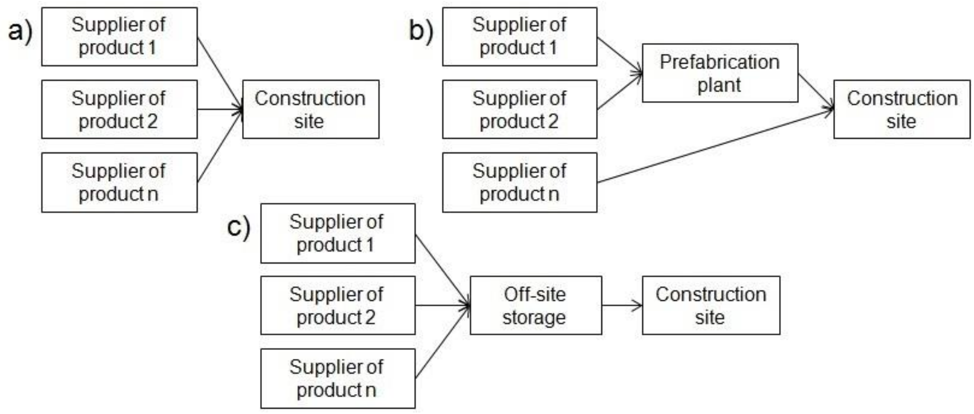

Fig. 2: Examples of construction material supply channels configuration

A project's demand for a particular material may be variable, which is related with the scope of works scheduled for consecutive periods. For instance, while erecting a framed structure of an in-situ reinforced concrete building, there will be periods of higher and lower demand for concrete mix – depending on what structural members, slabs or columns, are under construction at the moment. In such cases, it is possible to supply the projects from different sources: using e.g. cheaper source of low capacity in the periods of low demand, and switching to more expensive sources of higher capacity (or to a number of sources) as demand gets higher. The capacities of selected suppliers may change over time, and new suppliers with competitive offer may emerge. Therefore, the project supply channels, even regarding the same material, do not have to be decided once and for all.

Another thing is worth considering while taking logistic decisions: the possibility to substitute materials, components or construction methods. This may involve changes to the scope of on-site operations. This is a standard practice, especially with the growing popularity of Design-Build or other procurement systems empowering the contractor to search for optimal design solutions. Substitution increases the constellation of possible supply channels to be considered.

As a result, many options need to be considered in search of most efficient supply chains. To facilitate the process, mathematical models are being constructed and they should allow for the real-life complexity and dynamics. The purpose of this paper is to analyse and model the construction project's material supply chains to support logistic decisions.

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

The literature provides an abundance of supply chain selection guidelines and models aimed at supporting decisions in this respect. The concept of a project's logistic management needs to allow for case-specific objectives and constraints, and the criteria worth considering in the process are numerous. For instance, Chen [4] lists as many as 23 such criteria, with the most important being the price, ability to deliver on time, quality, disposing of equipment and capabilities, geographic location, technical capabilities, management and organization, industrial reputation, financial situation, historical performance, maintenance service, service attitude, and packing ability.

Many mathematical models of supplier selection are aimed at ranking the suppliers for one transaction with the assumption that the conditions they offer and their capabilities are fixed [5, 6]. The best supplier is the one that fulfils all or the largest number of criteria. However, examples presented in the introduction indicate that the decision model should allow for the project's variable demand, variable supplier capacities, possibility of switching to substitutes and covering the demand from a number of sources, and a number of approaches that cover all or some of these aspects are present in the literature. A mixed integer non-linear formulation of dynamic supplier selection problem can be found, among others, in [7]: 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, and are specific to each supplier. Chern and Hsieh [8] present and compare 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 analyze complex supply networks and focus on quantity discounts. In search for solutions, the authors use heuristic algorithms and compare a number of multi-objective programming approaches.

Substitution of materials is usually a result of supply shortages or searching for economies, but other benefits are referred to in the literature. For instance, Yu-Hsin Lin et al. [9] list and analyse 21 factors to be considered in decisions on material substitution, including environment protection. Substitution increases flexibility and is characteristic of agile supply networks operating in competitive markets. At the same time, it considerably increases the number of potential supply channels and makes decision-making process more complex. With a large number of variables to be considered, Luo et al. [10] put forward that artificial neural networks may be of great help.

An interesting contribution to construction-dedicated supply planning and optimization can be found in [11]. The author described and analysed a 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 during the planning horizon. The problem was formulated as an integer programming model, and the solving procedure is based on a linear programming-based heuristic.

The handful of works presented above is but a small part of the rich literature on the subject, presenting a broad scope of models differing in the level of complexity and solution methods. The model presented in the section to follow draws on them, but is based on the analysis of the typical supplier selection practices on Polish construction market.

3 METHODOLOGY

The authors analyse the decision problem of selecting supply channel and scheduling deliveries for a construction material from the point of a contractor. The material is understood in a broader context: as a raw material, product or component at any level of pre-processing used for construction purposes. The key assumptions are as follows:

- the material is consumed on construction site in a non-uniform manner, depending on the schedule of works;
- the possible supply channels to choose from are to be identified in advance; they vary in the following qualities: the set of supply channel participants, offered material type (original or substitute, unprocessed or at various levels of pre-processing which reduces effort on construction site), location and capacity of material storage areas; as a consequence, the supply channels are characterised by various transaction costs, transportation cost, the price of the material itself, and additional cost of material handling or preparation on site;
- if economically justified, the material may be hoarded and stored not only on construction site, but also in other locations, which involves additional storage and transportation cost.

The problem consists in defining economically justified quantities that should be delivered by particular supply channels. To solve it, the authors propose a mixed integer linear programming model capable of optimizing supplies with materials consumed irregularly, enabling the user to determine economic order quantities for consecutive periods of construction works and to choose from available supply channels of a particular material/component or its substitutes, if applicable.

4 RESULTS

The result of the analysis is a mathematical model of the problem. The model is to be applicable to minimizing total inventory management cost including costs of on-site pre-processing. The model can be solved by means of widely available software, such as Excel Solver, Lingo, Lp_Solve. Construction of the model is presented below.

The whole planning horizon, *T*, was divided into *n* periods. The durations of these periods are, consecutively, t_i, $i = 1, 2, ..., n$ ($T = \sum_{i=1}^{n} t_i$). Deliveries of the analyzed material are to occur at the beginning of these periods. There exist *m* possible supply channels that differ in the source (the supplier) and location of storage area (on-site storage or ancillary storage). Thus, in the set of all available supply channels, $I = \{1, 2, ..., m\}$ one can distinguish two subsets: I_1 that use only on-site storage, and I_2 that use intermediate storage outside the construction site. There is a set *R* of pairs of supply channels – these pairs use the same source of the material. Some of these sources offer substitute materials, so not identical with those in the project specification, but fulfilling all requirements. The set of sources of substitute materials is *U*.

The following parameters characterize each supply channel: d_{ij} – capacity of the supplier so the maximum quantity that can be delivered by channel *j* ($j = 1, 2, ..., m$) within period i ($i = 1, 2, ..., m$), c_{ij} – unit price of the material delivered by channel j ($j = 1, 2, ..., m$) within period i ($i = 1, 2, ..., m$), k_{rj} – the cost of performing one delivery by channel j (this cost is assumed to be irrespective of the delivered quantity), k_{tj} – unit transportation cost of delivery by channel j, and k_{aj} – unit cost of handling and pre-processing the material delivered by channel *j* (includes transportation from ancillary storage area to the construction site, on-site assembly etc. – if applicable).

The batch size of the material delivered by channel j in period i is S_{ij}, $i = 1, 2, ..., n$, $j = 1, 2, ..., m$. In the case of substitute materials whose delivery would be measured in different units, the batch size must be expressed in the units applicable for the basic material.

The as-planned material consumption for period i is q_i; it is defined on the basis of the schedule of works. The stock v_{ij} of the material delivered by channel j to the construction site at the beginning of period i, excluding the just delivered S_{ij} can be calculated according to the following formulas:

$$v_{1j} = 0, \quad j = 1, 2, ..., m, \tag{1}$$

$$\sum_{j=1}^{m} v_{i+1,j} = \sum_{j=1}^{m} \left(S_{ij} + v_{ij}\right) - q_i, \quad i = 1, 2, ..., n-1. \tag{2}$$

This quantity represents the difference between the stock quantity at the previous period increased by a delivery completed in this previous period, and the quantity consumed in the previous period. Equation (1) indicates that at the beginning of the planning horizon no material was in stock.

The quantity to be delivered is to be calculated with consideration to the following:

- the delivery is a non-negative value and does not exceed the supply channel capacity at period *i*:

$$0 \le S_{ij} \le d_{ij}, \ \ i = 1, 2, ..., n, \ \ j = 1, 2, ..., m; \tag{3}$$

- in the case of supply channels that use the same source, the total quantity delivered by all of them cannot be greater than the source's capacity:

$$S_{ip} + S_{ir} \le d_{ip} = d_{ir}, \ \ i = 1, 2, ..., n, \ \ \forall (p, r) \in R; \tag{4}$$

- the total quantity delivered by all particular supply channels *j*, plus the quantity kept in stocks at the beginning of period *i*, is to satisfy the construction site's demand for this period and not to diminish the buffer stock, R_i, kept to mitigate risks of stock-out:

$$\sum_{j=1}^{m} \left(S_{ij} + v_{ij} \right) \ge q_i + R_i, \ \ i = 1, 2, ..., n-1; \tag{5}$$

- in the case of some periods $j = s, t, ..., u$, one may require that the demand is not covered by substitute materials, so:

$$\sum_{j \notin U} \left(S_{ij} + v_{ij} \right) \ge q_i + R_i, \ \ i = s, t, ..., u; \tag{6}$$

- as the project approaches the end of the planning horizon, all stocks need to be used up so that no material was left unconsumed; therefore the deliveries should be reduced by the quantity kept as buffer stocks:

$$\sum_{j=1}^{m} \left(S_{nj} + v_{nj} \right) = q_n. \tag{7}$$

The material is going to be delivered to storage areas – these are most likely not of unlimited capacity. Thus, the available areas are $F^1_{\max}$ (on-site storages), and $F^2_{\max}$ (ancillary storages). The gross size of storage areas required in the particular periods *i*, F_i^1, F_i^2 $(i = 1, 2, ..., n)$, can be calculated according to the following formulas:

$$F_i^1 = \sum_{j \in I_1} \frac{\alpha_j}{N_{smj}} \cdot \left(S_{ij} + v_{ij} \right), \ \ i = 1, 2, ..., n, \tag{8}$$

$$F_i^2 = \sum_{j \in I_2} \frac{\alpha_j}{N_{smj}} \cdot \left(S_{ij} + v_{ij} \right), \ \ i = 1, 2, ..., n, \tag{9}$$

where N_{smj} is the material-specific standard net square footage rate (units of material per unit of area), and α_j - an increasing factor that allows for areas for material handling operations [2]. Formulas (8) and (9) allow the planner to estimate storage area requirements – with the assumption that the deliveries arrive as a whole at the beginning of a period. If the delivery were to be spread over the period, the formulas need to be adjusted for this fact.

The required area of each storage F^1, F^2 is a maximum of storage areas calculated for each period, so:

$$F^1 = \max_{i=1,\,2,\,...,\,n} \{F_i^1\}, \tag{10}$$

$$F^2 = \max_{i=1,\,2,\,...,\,n} \{F_i^2\}. \tag{11}$$

However, the availability of space is not unlimited, therefore:

$$F^1 \le F_{\max}^1 , \tag{12}$$

$$F^2 \le F_{\max}^2 . \tag{13}$$

The process of supply channel selection presented in the steps to follow is based on the concept of economic order quantity to minimize total inventory management cost. Apart from the cost of the material itself, these are: opportunity cost, warehousing cost, ordering cost, transportation cost and on-site pre-processing cost. Especially in the case of materials used in large quantities and over long periods, these costs have a considerable share in the construction project budget.

The total value of the material purchased for the project is K_t :

$$K_t = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot S_{ij} , \tag{14}$$

The opportunity cost of keeping stocks, K_z, with the assumption that the contractor is paid only at the end of the planning horizon, can be calculated as follows:

$$\begin{cases} K_z = r \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot S_{ij} \cdot \Delta t_i \\ \Delta t_i = \sum_{k=i}^{n} t_k , \quad i = 1,\, 2,\, ...,\, n \end{cases} , \tag{15}$$

where *r* represents the expected rate of return.

In the case of construction projects, the cost of warehousing, K_s, is composed mostly of fixed cost of preparing the temporary storage facilities (works such paving open areas, erecting storage buildings, or fees for using someone else’s land). These may be related to the storage area:

$$K_s = k_s \cdot \left(F^1 + F^2\right), \tag{16}$$

where k_s stands for the unit cost of providing storage facilities (per unit of area).

Let’s assume that the buying cost, K_r, is composed of fixed costs and irrespective of batch size, including the cost of placing an order, testing the batch, weighting the delivered material, insuring the delivery, etc. It can be expressed as a product of k_{rj}, so a cost of one order as to be delivered by the channel *j*, and the number of deliveries, plus the total transportation costs and, if applicable, costs of pre-processing the delivered material:

$$K_r = \sum_{i=1}^{n} \sum_{j=1}^{m} k_{rj} \cdot x_{ij} + \sum_{i=1}^{n} \sum_{j=1}^{m} \left(k_{tj} + k_{aj}\right) \cdot S_{ij} . \tag{17}$$

As the number of deliveries is unknown, the buying cost was expressed as a function of a binary variable x_{ij} that assumes the value of 1 if the delivery in period *i* comes from the supply chain *j* (so if $S_{ij} > 0$), and equals 0 in other case (so if $S_{ij} = 0$). Therefore, x_{ij} depends on the unknown variables that represent the batch quantity. The model allows for this fact by means of an additional constraint that enforces fulfilling the above implications when the binary variable is to be minimized in the objective function:

$$S_{ij} \le M \cdot x_{ij}, \; i = 1, 2, ..., n, \;\; j = 1, 2, ..., m, \tag{18}$$

where M is a sufficiently large number.

The mathematical formulation of the problem is expressed as a linear programming problem of determining the economically justified material quantities that should be delivered by particular supply channels. It comprises the objective function, boundary conditions and constraints described by linear analytic relationships. The objective function assumes the following form:

$$\min K: \quad K = K_t + K_z + K_s + K_r. \tag{19}$$

To summarize, the feasible solutions are to fulfil all constraints explained above:

$$K_t = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot S_{ij}$$

$$K_z = r \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot S_{ij} \cdot \Delta t_i$$

$$\Delta t_i = \sum_{k=i}^{n} t_k, \; i = 1, 2, ..., n$$

$$K_s = k_s \cdot \left(F^1 + F^2\right)$$

$$K_r = \sum_{i=1}^{n} \sum_{j=1}^{m} k_{rj} \cdot x_{ij} + \sum_{i=1}^{n} \sum_{j=1}^{m} \left(k_{tj} + k_{aj}\right) \cdot S_{ij}$$

$$S_{ip} + S_{ir} \le d_{ip} = d_{ir}, \; i = 1, 2, ..., n, \; \forall (p, r) \in R$$

$$S_{ij} \le M \cdot x_{ij}, \; i = 1, 2, ..., n, \;\; j = 1, 2, ..., m$$

$$v_{1j} = 0, \;\; j = 1, 2, ..., m$$

$$\sum_{j=1}^{m} v_{i+1, j} = \sum_{j=1}^{m} \left(S_{ij} + v_{ij}\right) - q_i, \; i = 1, 2, ..., n-1$$

$$\sum_{j=1}^{m} \left(S_{ij} + v_{ij}\right) \ge q_i + R_i, \; i = 1, 2, ..., n-1$$

$$\sum_{j \notin U} \left(S_{ij} + v_{ij}\right) \ge q_i + R_i, \; i = s, t, ..., u$$

$$\sum_{j=1}^{m} \left(S_{nj} + v_{nj}\right) = q_n$$

$$F_i^1 = \sum_{j \in I_1} \frac{\alpha_j}{N_{smj}} \cdot \left(S_{ij} + v_{ij}\right), \; i = 1, 2, ..., n$$

$$F_i^2 = \sum_{j \in I_2} \frac{\alpha_j}{N_{smj}} \cdot \left(S_{ij} + v_{ij}\right), \ i = 1, 2, ..., n$$

$$F^1 \geq F_i^1, \ i = 1, 2, ..., n$$

$$F^2 \geq F_i^2, \ i = 1, 2, ..., n$$

$$F^1 \leq F_{\max}^1$$

$$F^2 \leq F_{\max}^2$$

The feasible solutions are also to meet the following boundary conditions:

$$0 \leq S_{ij} \leq d_{ij}, \ i = 1, 2, ..., n, \ \ j = 1, 2, ..., m \tag{20}$$

$$x_{ij} \in \{0, 1\}, \ i = 1, 2, ..., n, \ \ j = 1, 2, ..., m \tag{21}$$

The relationships (10) and (11) have been modified to the equivalent linear form of inequalities on the basis of the following assumption: the maximum storage area, which is to be minimized to save on storage cost, equals at least the required storage area in each particular period.

5 DISCUSSION

To illustrate the application of the model, it was used to plan deliveries of aggregate for a notional case of constructing a road sub-base. Let us assume that, according to the specification, the aggregate should be a natural crushed stone. It can be substituted with recycled concrete, this however requires additional on-site operations related with stabilizing the embankment.

Table 1 lists the demand for the aggregate in consecutive periods (weeks) of the planning horizon together with required buffer stocks whose size was established on the basis of risk analysis (not the subject of this analysis).

Tab. 1: Quantities of material required in consecutive periods of analysis

Demand	**Period *i***					
	1	2	3	4	5	6
As-planned consumption, q_i (t)	1000	600	1500	1000	600	900
Buffer stock, R_i (t)	100	60	150	100	60	0

Table 2 lists the parameters of available supply channels. Channel 1 provides reclaimed concrete aggregate that is cheap but requires additional pre-processing. All remaining channels deliver natural crushed stone. Channels 4 and 6 would deliver to the ancillary storage of maximum area of 2000 m^2 (in this case, the cost k_{aj} represents the cost of additional loading and transport from the ancillary storage to the construction site). Other channels deliver to smaller storage areas (400m^2 each) located directly along the constructed road. Channels 3 and 4 use the same source, similarly channels 5 and 6.

Both the basic material and the substitute have the same standard net square footage rate (units of material per unit of area), $N_{smj} = 3\, m^2 / t$, and the increasing factor that allows for areas for material handling operations $\alpha_j = 1{,}2$. For both materials the unit cost of providing storage facilities is $k_s = 1$ €/m^2. The interest rate for calculating opportunity cost, expressed per unit of time representing the period of analysis, is $r = 0{,}25\,\%$. It was assumed that only natural aggregate is to be used for works in period no. 4.

The problem was solved by means of LINGO 12.0 Optimization Modeling Software. The results – so the optimal selection of supply channels and quantities of materials delivered by them in the consecutive periods – are presented in Table 3.

Tab. 2: Quantities of material required in consecutive periods of analysis

j	**Maximum delivery quantity per period *i* (t)**						**Price of material in period *i* (€/t)**						k_{rj} (€/ delivery)	k_{tj} (€/t)	k_{aj} (€/t)
	1	2	3	4	5	6	1	2	3	4	5	6			
1	0	500	500	500	500	0	-	7	7	7	7	-	12	2	0,2
2	500	400	400	300	0	0	10	10	10	10	-	-	10	1	0
3	700	700	700	700	700	700	9	10	11	11	11	11	10	1,2	0
4	700	700	700	700	700	700	9	10	11	11	11	11	10	1,1	0,3
5	600	600	600	600	600	600	10	11	11	10	10	10	10	1,1	0
6	600	600	600	600	600	600	10	11	11	10	10	10	10	1	0,3

Tab. 3: Solution of the example case

Channel *j*	Quantities to be delivered in each period *i*, (t)					
	1	2	3	4	5	6
1	0	500	500	500	500	0
2	500	400	400	300	0	0
3	300	100	0	0	0	0
4	400	0	0	0	0	0
5	200	0	0	200	0	400
6	0	0	0	400	0	0

The total cost of the material and inventory management of the optimal solution is 59 120 € (K_t=49 300 €, K_z=502 €, K_s=680 €, K_r=8638 €). The required area of on-site storage is F^1=400 m^2. The material deposited in the ancillary off-site storage area needs F^2=280 m^2, and this storage is to be supplied only at the first and the fourth period. The cheaper substitute (reclaimed concrete) is in this case to be delivered whenever available and at the maximum capacity of its source. The quantities collected as inventory enable the works of the fourth period to be completed as required by the initial assumptions – using only the natural aggregate.

6 CONCLUSION

In supply chain management, the mathematical models' practicability depends on their ability to allow for real-life conditions of business operations. The literature on supply logistics focuses on production and retail related models with their typical constraints. Construction projects are different in character. Their main features are unrepeatability in terms of scope of works (and thus the selection of required materials and components), location (project-specific transportation routes, custom-made temporary stacking areas), and constellation of suppliers (wide ranges of materials and components to be supplied from a large number of sources whose selection is project-specific and not likely to repeat again). Thus, the logistic models proven in production and retail environment are not directly applicable to construction projects.

Though mathematical modelling has not been popular in construction supply chain management in construction yet [12], the growing complexity of logistic chains, especially in the case of large scale projects, and market-enforced search for economies by competing organisations will inevitably lead to adopting optimisation tools in practice. The mixed integer linear programming model presented in the paper, despite its relative complexity, can be used for finding optimal solutions even by means of widely available computer spreadsheets and solvers. No special knowledge on optimization theories and algorithms nor creating dedicated software is needed to use it.

The problem presented in the paper was limited to selecting supply channels providing one type of material, but the method can be used for integrated sourcing and delivery planning of any materials and components that require additional pre-processing or handling on- or off-site, may be replaced with substitutes (which again may involve additional handling), and can be stored in quantities exceeding current demand.

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