Inzinerine Ekonomika-Engineering Economics, 2014, 25(1), 13–20

Decision Model for Selecting Supply Sources of Road Construction Aggregates

Piotr Jaskowski[1], **Anna Sobotka**[2], **Agata Czarnigowska**[3]

[1,3]Lublin University of Technology
Nadbystrzycka ul. 40, Lublin, 20-618, Poland
E-mail. p.jaskowski@pollub.pl, a.czarnigowska@pollub.pl

[2]AGH University of Science and Technology
A. Mickiewicza al. 30, Kraków, 30-059, Poland
E-mail. sobotka@agh.edu.pl

crossref http://dx.doi.org/10.5755/j01.ee.25.1.3595

The authors' recent survey on Polish road contractors' aggregate procurement methods indicates that optimization techniques are rarely used in practice – despite the fact that the material is to be transported from large distances and its sources are inconveniently distributed throughout the country. In search for economy in this respect, the authors propose mixed binary linear programming models to facilitate the contractor's logistic decisions. The purpose of these models is to find delivery quantities from a number of supply locations (of limited capacity and with a limited transportation potential) to predefined destinations along the road in a way that minimizes logistic costs. The problem considered is an extension to the classic transshipment problem, and allows for change of delivery destination along the route with the progress of works, and for constraints resulting from the schedule of the works.

Keywords: *transshipment problem, supply chain management, road construction, schedule constraints.*

Introduction

Road works and demand for aggregates

Recent Polish road infrastructure boom was triggered by introduction of European Union operating programs. According to information on national road projects by the Polish Ministry of Transport, Construction and Maritime Economy, (www.transport.gov.pl/2-48203f1e24e2f-1793180-p_1.htm), in March 2012, works related solely with national roads covered 1358 km, 528 km of which were motorways. This unprecedented scale of investment in road projects running in parallel is illustrated by Figure 1 that presents location of most important national roads scheduled to be constructed between 2011 and 2015. The figure shows only motorways and dual carriageways: at the same time, there are numerous regional and local road projects underway. Thus, a great number of projects run concurrently throughout the country.

Road construction consumes large quantities of aggregates. If the material is not available easily and if it is to be transported from large distances, as in the case of Poland, careful selection of material sources and coordination of deliveries with construction schedules become key factors of project performance. Though many projects have been already completed, rough estimates of Polish Association of Aggregate Suppliers (Kabzinski, 2012) on the national road project-related demand for aggregates indicate that still about 12 million tons of high-quality natural aggregates a year will be required in 2013. In Poland, natural aggregate sources are unevenly distributed across the country – practically all rock deposits are located south from the line connecting Wroclaw and Kielce (marked with a dotted line in Figure 1), but sands and gravels – to the north. This makes material handling a key issue while planning large-scale engineering works. The condition of transport routes adds to the problem: existing roads are of low carrying capacities, and there are numerous traffic disruptions due to many roads under construction. The rail network is not dense enough to provide an adequate service.

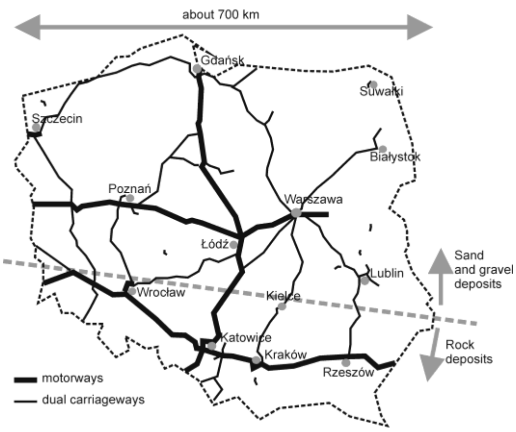

Figure 1. Motorways and dual carriageways completed, under construction and planned for tender in 2011–2015 vs. distribution of natural resources (based on information published by Polish General Directorate of National Roads and Highways, http://www.gddkia.gov.pl/1037/sprawdz-na-mapie-przygotowanie-drog-i-autostrad, accessed in April 2013)

It is thus advisable to improve aggregate procurement practices – to make the best use of available resources and minimize the burden of construction logistics – especially in the times of tough competition for contracts and resulting low profit margins. Surprisingly, the authors' recent pilot survey on major road contractors' material procurement practices indicates that mathematical optimization tools are rarely used (Sobotka *et al.*, 2012). This provides rationale for proposing tools that facilitate logistic decisions.

Material supply management in construction

Effective supply chain management (SCM) is considered a key determinant of competitiveness and success for most manufacturing and retailing organizations. It also finds application in project-oriented environments as construction (O'Brien *et al.*, 2008), where organization and material sourcing is becoming increasingly complex, competition is becoming tougher, and the client's expectations towards quality, cost, and delivery times are growing. Implementing supply chain management is argued to have a significant impact on cost, service level, and quality (Chiou, 2008; Abduh *et al.*, 2012).

SCM involves, among others, selection of reliable business partners (Brauers *et al*., 2008; Zavadskas *et al.*, 2010; Plebankiewicz 2012, Smeureanu *et al.*, 2012; Zolfani *et al.*, 2012), which is usually a complex multicriteria problem (Zavadskas & Turskis, 2011; Liou & Tseng, 2012). The chains, once constructed, should be checked in terms of their overall performance (Pan, Lee & Chen, 2011). Success of the chain's operation depends on the reliability and accuracy of information exchange, therefore techniques that enhance inter- and intra-organizational information flows are being developed (Ren *et al.*, 2012; Danso-Amoako, O'Brien & Issa, 2004; Ren 2011; Yuan Chen, 2011; Tambovcevs, 2012).

Materials management is one of the most important aspects of construction SCM. Research on construction projects inventory optimization is aimed at providing guidelines for on-site construction material management (Thomas, Riley & Messner, 2005); numerous works have been devoted to optimization of construction site layouts (El-Gafy & Ghanem, 2010, Huang, Wong & Tam, 2010) to minimize material handling.

On the one hand, excessive inventories mean high holding costs. On the other hand, material shortages may cause serious disruptions in construction process, often not in proportion to the delay of the delivery, and result in contractual penalties and losses on work stoppage. Wrong decisions on inventories seriously affect on-site productivity (Thomas *et al.*, 1989; Thomas *et al.*, 1999; Thomas & Horman, 2005) – which provides arguments for research in the field of mathematical inventory modeling. Inventory sizing and scheduling deliveries are therefore subject to economic analysis aimed at finding inventory levels that assure continuity of works at minimum cost. In many cases, methods and models used for batch sizing and delivery scheduling meant for high-volume industrial production can be applied to planning deliveries for construction projects.

The Just-in-Time (JIT) approach with material deliveries arriving exactly at the moment they are required eliminates storing cost. However, it requires full commitment of suppliers and efficient information exchange, and that means increased transport cost, and vulnerability to disruptions. Potential benefits of JIT strategy in construction were discussed e.g. by Polat & Arditi (2005), and Shmanske (2003).

The Economic Order Quantity (EOQ) concept, probably the most popular in inventory management, allows for the relationship between storage and order cost according to the lot size, and assumes constant demand for the material.

To adjust the inventory sizing models to more real-life cases with demand that varies with time, numerous algorithms were proposed, such as Lot-For-Lot (analysed by e.g. Grubbstrom & Tang 2012), Least Unit Cost Heuristic, Least Total Cost Heuristic (Vollmann Berry & Whybark, 1997), Wagner-Within Algorithm, or Silver-Meal Heuristic (discussed e.g. by Sanchez *et al*., 2001, Vargas & Metters, 2011).

Construction project supply plan is usually subordinated to the schedule of construction processes. There is an abundance of project scheduling algorithms that allow for resource constraints and uncertainties and disruptions due to e.g. delayed supplies (Biruk & Jaskowski, 2008; Jaskowski & Biruk, 2011; Jaskowski & Sobotka, 2012). However, there seems to be few publications that combine construction scheduling with supply scheduling and investigate into the problem of planning material deliveries in the case of building sites of limited storage space (Said & El-Rayes, 2011).

Aim of research

The authors aim to propose a mathematical model and a method for solving a particular problem of handling deliveries for a road construction project – in particular, supplying aggregates for a granular sub-base of a road that is to be constructed according to its particular schedule of works. The aim of the analysis is to find delivery quantities from a number of suppliers (of limited capacity and with a limited transportation potential) to predefined destinations along the road in a way that minimizes logistic costs. The aim of the authors is to allow for change of delivery destinations along the road under construction – with the progress of works, and for constraints resulting from the schedule of the works.

In the analyzed case, the supply chain that provides the material is simple (Figure 2), but corresponds to the road-building practice. It comprises suppliers (a number of aggregate quarries) who deliver the same type of material to stacking areas (intermediate stops for shipments), from which it is taken to road sections under construction.

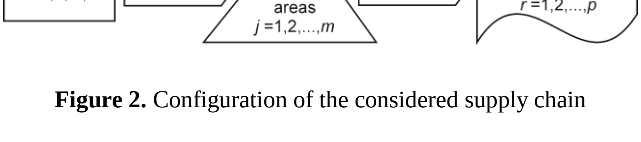

Figure 2. Configuration of the considered supply chain

Efficiency of the simple approaches to planning supplies (JIT, EOQ) is not guaranteed in practical cases, and it is not easy to propose universal guidelines for selection of a planning method that would produce most economic solution. Considering road construction, and supplying the works with large quantities of raw material, the most common JIT and EOQ concepts find little use: according to the authors' survey of road contractors current practices and analysis of conditions on the construction aggregates market (Sobotka *et al.*, 2012), the following was observed:

- as material is consumed in large quantities, there is a limitation of transporting capacity of suppliers who operate mostly by road, not rail;
- deliveries need to start prior to commencement with works that consume it: capacity of construction teams is greater than capacity of deliveries;
- as arises from the above, material stocks have to be maintained, but the capacity of storage near the areas of works is limited – intermediate storage is thus required.

These circumstances call for an original, dedicated management method. If it is to find practical application, it should preferably be simple and use widely available tools.

Logistic models of aggregate supply for road construction

Method

The problem considered is an extension to the transshipment problem (Orden, 1956). The transshipment problem itself is a modification of the classic transportation problem – introducing a set of transshipment points that can serve as intermediate stops for shipments. The objective in the transshipment problem is to determine how many units of material should be shipped from a particular source via a particular transshipment point to a particular destination, so that all destination demands are satisfied with the minimum possible transportation costs.

To solve it, the authors proposed mixed binary linear programming models – with the objective function that represents total shipping cost to be minimized, and with a set of constraints and boundary conditions reflecting the character of the problem. The complexity of the models representing the problem should be adequate to the aim of the research – it must cover the key factors in aggregate inventory management from the point of the assumed criterion of minimal logistic cost. Two models were proposed: Model I, more precise, requires considerable computational effort. Model II, being its simplification, can be solved quickly, but it assumes that daily deliveries were scheduled and optimized separately.

Model I

There exist, in total, n suppliers of the aggregate for granular sub-base course (i =1, 2, ..., n). The aggregate is to be delivered to stacking areas j, and their total number is m (j =1, 2, ..., m). From these stacking areas, the material is to be forwarded to the destination points – sections r of the road being constructed (r =1, 2, ..., p). The stacking areas and road sections should be numbered according to the sequence of works. The deliveries are made by means of trucks of equal load capacity. The remaining notations used in the model are listed below:

t_r is a completion date of the road section r =1, 2, ..., p, and the works in the next section start without any lag, so t_0 denotes the day of commencement with works in the first road section, and t_p – the day of completing the last section;

z_r is a daily consumption of aggregate in section r, expressed in units per day, where unit means the volume brought by a single truck;

c_{ij} represents the unit price of delivering one unit of aggregate from the supplier i to the stacking area j; it covers both the price of the material itself and transport cost, and is expressed in EUR per unit (truckload);

d_{ij} is a maximum daily volume of deliveries from supplier i reaching stacking area j, resulting from the quarry's daily production and loading capacity and travel distance, expressed in units (truckloads) per day;

k_{jr} is a unit transport cost from the stacking area j to the road section r, expressed in EUR per unit (truckload),

E is the advance of deliveries before commencement with works (t_0), expressed in days; during E days deliveries can be made just to stock;

S_j – the level of safety stock in the stacking area j, expressed in units (truckloads);

L_j – maximum capacity of stacking area j, expressed in units (truckloads);

x_{ij} – a variable that represents the quantity of aggregate delivered from the supplier i to the stacking area j, expressed in units (truckloads), it is no smaller than 0 for each supplier and each stacking area;

y_{jr} – a binary variable used for assigning stacking areas to particular road sections, it equals 1 if the aggregate for section r will be taken from stacking area j, and 0 – in another case.

$u_{ij\delta}$ – a binary variable that equals 1 if the aggregate is delivered from the supplier i to the stacking area j at the day δ, δ =-E+1, -E+2, ..., 0, 1, ..., t_p.

It was assumed that all the aggregate for a particular road section should come from the same stacking area, so

$$\sum_{j=1}^{m} y_{jr} = 1, \ \forall r = 1, 2, \ldots, p \tag{1}$$

The quantity of aggregate brought from the supplier i to the stacking area j is the sum of daily deliveries from i to j:

$$x_{ij} = \sum_{\delta=-E+1}^{t_p} u_{ij\delta} \cdot d_{ij}, \ \forall i = 1, 2, \ldots, n, \ \forall j = 1, 2, \ldots, m \tag{2}$$

Each stacking area j should receive the aggregate quantity corresponding to the consumption at the road sections it serves:

$$\sum_{i=1}^{n} x_{ij} \geq \sum_{r=1}^{p} y_{jr} \cdot z_r \cdot (t_r - t_{r-1}), \ \forall j = 1, 2, \ldots, m \tag{3}$$

The suppliers' production and transporting capacity is limited, so, on any particular day, a supplier cannot provide their maximum daily volume of deliveries to more than one stacking area:

$$\begin{aligned} &\sum_{j=1}^{m} u_{ij\delta} \leq 1, \\ &\forall i = 1, 2, \ldots, n, \\ &\forall \delta = -E+1, -E+2, \ldots, 0, 1, \ldots, t_p \end{aligned} \tag{4}$$

The stock level at a stacking area cannot be greater than the stacking area capacity, and cannot drop below safety stock level:

$$S_j \le \sum_{i=1}^{n} \sum_{\delta=-E+1}^{w} u_{ij\delta} \cdot d_{ij} - \sum_{r=1}^{p} y_{jr} \cdot z_r \cdot \omega \le L_j, \quad \forall j = 1, 2, \dots, m, \ \forall w = -E+1, -E+2, \dots, 0, 1, \dots, t_p, \tag{5}$$

where: $$\omega = \begin{cases} \min\{t_r, w\} - t_{r-1}, \ w > t_{r-1} \\ 0, \ w \le t_{r-1} \end{cases} \tag{6}$$

The objective function (minimizing the total cost of supplying aggregate to all road sections considered) takes the following form:

$$\min z: \ z = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot x_{ij} + \sum_{j=1}^{m} \sum_{r=1}^{p} k_{jr} \cdot y_{jr} \cdot z_r (t_r - t_{r-1}) \tag{7}$$

The model may account for smaller deliveries (i.e. providing less than maximal daily number of units from the source to the destination), but due to the fact that the number of variables and constraints is considerable, and the model described by equations (1) to (7) is in fact quite complex, it is necessary to develop dedicated heuristic or metaheuristic algorithms to use it for solving practical cases.

Model II

To reduce computational complexity of *Model I*, simplifying assumptions were introduced. Deliveries to the stacking areas are continuous from the time of the stacking area opening. After selecting who should supply particular stacking areas (so after solving Model II), schedules of deliveries to the stacking areas should be prepared separately – by means of solving "classic" stock management models to optimize logistic cost. Let us assume that:

ρ_j represent daily costs of maintaining the stacking area j, or are sufficiently small numbers,

D is the number of days of delivering the aggregate to stacking areas before commencement with works in the road sections served by these stacking areas,

g_{ij} is a variable that represents the number of days of delivering the aggregate from the supplier i to the stacking area j, $g_{ij} \in$ int, $g_{ij} \ge 0$,

T_j – a variable that stands for the date of the stacking area j opening to deliveries,

v_j – a variable that stands for the date of the stacking area j closing for deliveries.

Just as in the case of Model I, the aggregate for a particular road section should come from one stacking area, and each stacking area should receive the quantities corresponding to the requirements of the road sections it serves, so conditions (1) and (3) must be fulfilled, whereas the total quantity of aggregate to be delivered from supplier i to stacking area j can be calculated according to the following formula:

$$x_{ij} = g_{ij} \cdot d_{ij}, \ \forall i = 1, 2, \dots, n, \ \forall j = 1, 2, \dots, m \tag{8}$$

Let us assume the beginning of the planning horizon to be E days before commencement with works at the first road section. The updated section starting dates are thus:

$$t_r^E = t_r + E, \ \forall j = 0, 1, ..., p \tag{9}$$

The stacking area j closes (at v_j) after the works on road sections served by this stacking area are completed:

$$y_{jr} \cdot t_r^E \le v_j, \ \forall j = 1, 2, ..., m, \ \forall r = 1, 2, ..., p \tag{10}$$

$$v_j \le t_p^E, \ \forall j = 1, 2, ..., m . \tag{11}$$

$$v_{j-1} \le v_j - \sum_{r=1}^{p} y_{jr} \cdot (t_r - t_{r-1}), \ \forall j = 2, 3, ..., m \tag{12}$$

The date of the stacking area j opening (and the possibility to begin deliveries) is to occur no later than on D days from the commencement with works in road sections served by this stacking area. With the assumption on continuous deliveries, this is no later than D days before completing the works in the preceding sections, served by the preceding stacking areas:

$$0 \le T_j \le v_{j-1} - D, \ \forall j = 2, 3, ..., m \tag{13}$$

$$0 \le T_1 \le E - D \tag{14}$$

The time of a stacking area operation cannot be shorter than the time of accepting deliveries from the suppliers serving it:

$$g_{ij} \le v_j - T_j, \ \forall i = 1, 2, ..., n, \ \forall j = 1, 2, ..., m \tag{15}$$

Let us assume that each supplier starts delivering as soon as a stacking area opens. Thus, if a supplier serves a number of stacking areas, the date of finishing deliveries to a particular stacking area should be before starting supplies to the next stacking area:

$$T_j + g_{ij} \le T_{j+1}, \ \forall i = 1, 2, ..., n, \ \forall j = 1, 2, ..., m-1 \tag{16}$$

This condition guarantees that the supplier's capacity is not exceeded, and that there are no material shortages. With relatively small daily costs of maintaining a stacking area, it facilitates selection of cheapest suppliers – at the cost of extending the operating period of stacking areas. Detailed schedules to particular stacking areas can be optimized after selecting which supplier should deliver what quantities to which stacking area.

The objective function (minimizing cost of deliveries and maintaining the stacking areas) takes the following form:

$$\min z:$$

$$z = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot x_{ij} + \sum_{j=1}^{m} \sum_{r=1}^{p} k_{jr} \cdot y_{jr} \cdot z_r (t_r - t_{r-1}) + \sum_{j=1}^{m} \rho_j \cdot (v_j - T_j - D) \tag{17}$$

Example

Input for the example is listed in Tables 1, 2 and 3. A fixed daily demand of $z_r = 60$ truckloads per day was assumed. The daily costs of maintaining each of the three stacking areas is ρ_j = 20 EUR/day.

Table 1

Unit cost of transporting a truckload of aggregate from supplier *i* to a stacking area *j* c_{ij} (EUR/truckload, results from assumed distances) and maximum daily volume of delivery from supplier *i* to stacking area *j*, d_{ij} (truckloads); to save space, these two values shown in one table in the form: c_{ij} / d_{ij}

j \ *i*	1	2	3	4	5
1	242 / 30	230 / 22	260 / 30	270 / 30	280 / 30
2	238 / 40	235 / 20	264 / 20	250 / 40	270 / 40
3	238 / 40	236 / 20	255 / 30	250 / 40	266 / 40

Table 2

Dates of completing works (t_r) in each road section (*r*)

r	1	2	3	4	5	6	7	8	9	10	11	12
t_r	2	4	6	8	10	12	14	16	18	20	22	24

Table 3

Unit cost of delivering a truckload of aggregate from stacking area j to road section r, k_{jr} (EUR/truckload)

j \ *r*	1	2	3	4	5	6	7	8	9	10	11	12
1	0,7	0,3	0,1	0,3	0,5	0,7	0,9	1,1	1,3	1,5	1,7	1,9
2	1,1	0,9	0,7	0,5	0,3	0,1	0,3	0,5	0,7	0,9	1,1	1,3
3	1,7	1,5	1,3	1,1	0,9	0,7	0,5	0,3	0,1	0,3	0,5	0,7

Table 4

Optimal solution for the example (only values greater than 0 are shown)

Variable:	X_{11}	X_{12}	X_{13}	X_{21}	X_{22}	X_{23}	Y_{11}	Y_{12}	Y_{13}	Y_{14}
Value:	150	320	280	330	160	200	1	1	1	1
Variable:	Y_{25}	Y_{26}	Y_{27}	Y_{28}	Y_{39}	$Y_{3,10}$	$Y_{3,11}$	$Y_{3,12}$	v_1	v_2
Value:	1	1	1	1	1	1	1	1	18	26
Variable:	v_3	T_1	T_2	T_3	g_{11}	g_{12}	g_{13}	g_{21}	g_{22}	g_{23}
Value:	34	1	16	24	5	8	7	15	8	10
Objective function:										**340,924**

Deliveries may start no later than $D = 2$ days before starting works at each of road sections served by the stacking areas, and no earlier than $E = 10$ days before commencement with works. Each road section is 100 m long, and the road is a dual carriageway with two lanes in each direction, of average total width of 22 m. The sub-base material unit mass is 1.8 t/m^3. The sub-base was assumed to be 60 cm thick, so the estimated material consumption per section is about 120 truckloads (20 t trucks). The works in each road section were assumed to take two days (Table 2). The unit cost of transport is 1 EUR/km, the price of aggregate is the same by each supplier and equals 10 EUR/t.

Solution of Model II based on the above input values was found by means of LINGO®12.0 Optimization Modeling Software by Lindo Systems Inc. Values of the optimal solution are shown in Table 4 (only those greater than 0 were shown to save space).

In this particular case, the lowest total logistic costs are obtained if each of three stacking areas considered served 400 m of road (stacking area no. 1 – sections 1-4, stacking area no. 2 – sections 5-8, stacking area no. 3 – sections 9-12). Deliveries are to start 9 days before commencement with works (T_1=1).

The first stacking area should be supplied daily, until completion of the 4th road section. Deliveries from supplier no. 1 (lasting 5 days in total) can start later, at a date established separately by optimizing the cost of keeping stock at the stacking area no. 1.

Calculations for deliveries from supplier no. 1 to stacking area no. 3 are conducted similarly: as the total delivery time (7 days) is shorter than the opening time of stacking area no. 3 ($v_3 – T_3$ = 10), it is possible to schedule deliveries in a way that minimizes the cost of keeping inventory, considering continuous deliveries from supplier no. 2. As for stacking area no. 2, the deliveries from suppliers no. 1 and no. 2 should be scheduled within 10 days – economies could be sought in delivering daily volumes lower than top capacity of the suppliers.

Conclusions

Considering the current Polish conditions, rapid development of road infrastructure requires expanding production of aggregates and treating them as a strategic resource. According to commercial organizations, a lot can be done to make better advantage of available natural resources, recycled material, and resources considered now an industrial waste, to cover the demand in full without resorting to importation (Kabzinski, 2012). However, logistic challenges faced by road contractors indicate also that decision support tools should find their way to road building. Complex logistic chains, related with the necessity of finding numerous suppliers for large projects, and market-enforced search for economies by improving organization will inevitably lead to adopting mathematic optimization tools in practice.

The models presented in the paper reflect the practice of supplying road works with mass-consumed aggregates: after determining the sources of material and quantities to be delivered by them, detailed delivery schedules are developed. Despite their being a far going simplification (deterministic parameters such as daily demand – related with fixed daily production, linear relationships), the models are considered at least adequate in describing reality – and providing values of decision variables required in supply management. Considering the scale of road and rail projects, considerable savings can be done by even small improvement of supply practices. Therefore, models of this kind may be welcome by practitioners and are likely to be further developed.

Acknowledgements

This work was financially supported by Ministry of Science and Higher Education in Poland within the statutory research number S/63/2013 (Lublin University of Technology) and 11.11.100.197 (AGH University of Science and Technology). The authors gratefully acknowledge the support.

References

Abduh, M., Soemardi, B. W., & Wirahadikusumah, R. D. (2012). Indonesian construction *supply chains cost structure and factors: a case study of two projects. Journal* of Civil Engineering and Management 18(2), 209–216. doi:10.3846/13923730.2012.671259.

Biruk, S., & Jaskowski, P. (2008). Simulation Modelling Construction Project with Repetitive Tasks Using Petri Nets Theory. *Journal of Business Economics and Management* 9(3), 219–226. doi: 10.3846/1611-1699.2008.9.219-226.

Brauers W. K. M., Zavadskas E. K., Turskis, Z., & Vilutiene, T. (2008). Multi-objective contractor's ranking by applying the Moora method. *Journal of Business Economics and Management* 9(4), 245–255. doi: 10.3846/1611-1699.2008.9.245-255.

Chiou, Chuang-Chun. (2008). Transshipment Problems in Supply Chain Systems: Review and Extensions. In Kordic V. (Ed.) Supply Chain (pp. 427–448). InTech, doi: 10.5772/5353.

Danso-Amoako, M., O'Brien, W., & Issa, R. (2004). A Case Study of IFC and CIS/2 Support for Steel Supply Chain Processes. In Beucke K.E. (Ed.) Proceedings of the 10th International Conference Computing in Civil and Building Engineering (ICCCBE-10), Weimar, June 2-4, (pp. 1–12). Weimar: Bauhaus-Universität Weimar Univ.-Verlag.

Grubbstrom, R. W., & Tang, O. (2012). The Space of Solution Alternatives in the Optimal Lot Sizing Problem for General Assembly Systems Applying MRP Theory. *International Journal of Production Economics* 140, 765–777. doi: 10.1016/j.ijpe.2011.01.012.

Huang, C., Wong, C. K., & Tam, C. M. (2010). Optimization of material hoisting operations and storage locations in multi-storey building construction by mixed-integer programming. *Automation in Construction* 19(5), 656–663. http://dx.doi.org/10.1016/j.autcon.2010.02.005

Jaskowski, P., & Biruk, S. (2011). The Method for Improving Stability of Construction Project Schedules through Buffer Allocation. *Technological and Economic Development of Economy*, 17(3), 429–444. doi: 10.3846/20294913. 2011. 580587.

Jaskowski, P., & Sobotka, A. (2012). Using Soft Precedence Relations for Reduction of the Construction Project Duration. *Technological and Economic Development of Economy*, 18(2), 262–279. doi: 10.3846/20294913.2012.666217

Kabzinski, A. (2012). Prognoza potrzeb i produkcji kruszyw w Polsce w latach 2012 – 2020 (+2) (Forecast of Aggregate Demand and Production in Poland in 2012-2020 (+2), in Polish). *Nowoczesne Budownictwo Inzynieryjne* 45(6), 84–89.

Liou, J. J. H., & Tzeng, G. H. (2012). Comments on "Multiple criteria decision making (MCDM) methods in economics: an overview". *Technological and Economic Development of Economy*, 18(4), 672–695. doi: 10.3846/20294913. 2012.753489.

Orden, A. (1956). The Transshipment Problem. *Management Science*, 2(3), 276–285. http://dx.doi.org/10.1287/ mnsc.2.3.276

Pan, N. H., Lee, M. L., & Chen, S. Q. (2011) Construction Material Supply Chain Process Analysis and Optimization. Journal of Civil Engineering and Management, 17(3), 357–370. doi:10.3846/13923730.2011.594221

Plebankiewicz, E. (2012). A fuzzy sets based contractor prequalification procedure. *Automation in Construction* 22, 433–443. http://dx.doi.org/10.1016/j.autcon.2011.11.003

Polat, G., & Arditi, D. (2005). The JIT Materials Management System in Developing Countries. *Construction Management and Economics* 23 (7), 697–712. http://dx.doi.org/10.1080/01446190500041388

Ren, Z. C. A. (2011). RFID-Facilitated Construction Materials Management (RFID-CMM) – A Case Study of Water-supply Project. *Advanced Engineering Informatics* 25, 198–207. doi: 10.1016/j.aei.2010.02.002

Ren, Y., Skibniewski, M. J., & Jiang, S. (2012). Building information modeling integrated with electronic commerce material procurement and supplier performance management system. *Journal of Civil Engineering and Management* 18(5), 642–654. doi: 10.3846/13923730.2012.719835.

Said, H., & El-Rayes, K. (2011). Optimizing Material Procurement and Storage on Construction Sites. *Journal of Construction Engineering and Management*, 137(6), 421–431. doi:10.1061/(ASCE)CO.1943-7862.0000307

Sanchez, S. N., Triantaphyllou, E., Webster, D. B., & Liao, T. W. (2001). A Study of the Total Inventory Cost as a Function of the Reorder Interval of Some Lot-sizing Techniques Used in Material Requirement Planning Systems. *Computers & Industrial Engineering*, 40(1-2), 101–116. http://dx.doi.org/10.1016/S0360-8352(00)00079-6

Shmanske, S. (2003). JIT and the Complementarity of Buffers and Lot Size. *American Business Review*, 21(1), 100–106.

Smeureanu, I., Ruxanda, G., Diosteanu, A., Delcea, C., & Cotfas, L.A. (2012). Intelligent agents and risk based model for supply chain management. *Technological and Economic Development of Economy*, 18(3), 452–469. http://dx.doi.org/10.3846/20294913.2012.702696

Sobotka, A., Walach, D., Pawlus, D., & Czarnigowska, A. (2012): Survey on projects supply chain in Polish road construction. Proceedings of Creative Construction Conference 2012: June 30–July 3, Budapest, Hungary, 636–645.

Tambovcevs, A. (2012). ERP system implementation in Latvian manufacturing and construction company. *Technological and Economic Development of Economy*, 18(1), 67–83. http://dx.doi.org/10.3846/20294913.2012.661176

Thomas, H. R., & Horman, M. J. (2005). Role of Inventory Buffers in Construction Labor Performance. *Journal of Construction Engineering and Management*, 131(7), 834–843. http://dx.doi.org/10.1061/(ASCE)0733-9364(2005) 131:7(834)

Thomas, H. R., Riley, D. R., & Messner, J. I. (2005). Fundamental Principles of Site Materials Management. *Journal of Construction Engineering and Management* 131(7), 808–815. http://dx.doi.org/10.1061/(ASCE)0733-9364 (2005)131:7(808)

Thomas, H. R., Riley, D. R., & Sanvido, V. E. (1999). Loss of Productivity Due to Delivery Methods and Weather. *Journal of Construction Engineering and Management*, 125(1), 39–46. http://dx.doi.org/10.1061/(ASCE)0733-9364(1999)125:1(39)

Thomas, H. R., Sanvido, V. E., & Sanders, S. R. (1989). Impact of material management on productivity – A case study. *Journal of Construction Engineering and Management*, 115 (3), 370–384. http://dx.doi.org/10.1061/(ASCE)0733-9364(1989)115:3(370)

Vargas, V., & Metters, R. (2011). A Master Production Scheduling Procedure for Stochastic Demand and Rolling Planning Horizons. *International Journal of Production Economics*, 132, 296–302. doi: 10.1016/j.ijpe.2011.04.025.

Vollmann, T. E., Berry, W. L., & Whybark, D. C. (1997). Manufacturing Planning and Control Systems, 4th ed. New York: McGraw-Hill.

Yuan Chen, J. M. (2011). A framework for using mobile computing for information management on construction sites. *Automation in Construction*, 20, 776–788. http://dx.doi.org/10.1016/j.autcon.2011.01.002

Zavadskas, E. K., Vilutiene, T., Turskis, Z., & Tamosaitiene, J. (2010). Contractor Selection for Construction Works by Applying SAW-G and TOPSIS GREY Techniques. *Journal of Business Economics and Management*, 11(1), 34–55. 10.3846/jbem.2010.03

Zavadskas, E. K., & Turskis, Z. (2011). Multiple criteria decision making (MCDM) methods in economics: an overview, *Technological and Economic Development of Economy*, 17(2), 397–427. doi: 10.3846/20294913 .2011.593291.

Hashemkhani Zolfani, S., Chen, I. S., Rezaeiniya, N., & Tamosaitiene, J. (2012). A hybrid MCDM model encompassing AHP and COPRAS-G methods for selecting company supplier in Iran. *Technological and Economic Development of Economy*, 18(3), 529–543. doi: 10.3846/20294913.2012.709472.

Piotr Jaśkowski, Anna Sobotka, Agata Czarnigowska

Tiekimo šaltinių pasirinkimo modelis tiesiant kelius

Santrauka

Autorių atliktas naujausias Lenkijos kelių tiesimo rangovų bendro tiekimo metodų tyrimas rodo, kad optimizacijos metodai yra retai naudojami praktikoje, nepaisant to, kad medžiagas reikia transportuoti ilgais atstumais ir jų šaltiniai yra nepatogiai išsidėstę po visą šalį. Išleista keletas publikacijų, kuriose statybos darbų grafikai yra suderinami su tiekimo grafikais ir kurios nagrinėja medžiagų pristatymo planavimo problemą, kai darbų vietose negalima palikti daug atsargų . Įvairių, tiekimą planuojančių metodų nauda praktikoje neturi garantijų, todėl autoriai siūlo du p-modelius ir sprendimo metodus, skirtus spręsti problemas, susijusias su konkrečiai kelių tiesimo projektu ir medžiagų pristatymu. Šių modelių tikslas yra išsiaiškinti medžiagų pristatymo kiekius ir nustatyti geriausias tiekimo vietas, taip sumažinant išlaidas tiesiant kelius. Norėdami išspręsti šią problemą, autoriai pasiūlė mišrius dvejetainius (binarinius) linijinius programavimo modelius.

Pirmasis modelis daro prielaidą, kad iš viso egzistuoja *n* skaičius tiekėjų *i*. Viskas turi būti pristatyta į perkrovimo vietas *j*, o šių vietų bendras skaičius yra *m.* Tada medžiagos persiunčiamos į reikiamas vietas – tiesiamo kelio sekcijas *r* (iš viso *p*). Perkrovimo vietos ir kelio sekcijos yra sunumeruojamos pagal darbų seką. Pristatymai atliekami vienodos krovos galios sunkvežimiais. Kiekvienai kelio sekcijai yra priskirta užbaigimo data, t_r, pagal darbų grafiką ir darbai vykdomi nuo sekcijos iki sekcijos be vėlavimų (t_0 reiškia darbų pradžią pirmojoje kelio sekcijoje, t_p – užbaigimo diena paskutinėje sekcijoje). Bendras kasdieninis medžiagų sunaudojimas sekcijai yra z_r, išreikštas pilnais sunkvežimiais per dieną. Vieno, medžiagų pilno sunkvežimio pristatymo kaina nuo tiekėjo *i* iki perkrovimo vietos *j*, c_{ij}, apima ir medžiagų, ir transporto kainas. Kasdieninė pristatymų iš tiekėjo *i* iki perkrovimo vietos *j* apimtis nėra didesnė už d_{ij}. Medžiagų vieneto pristatymo pilnu sunkvežimiu kaštai iš perkrovimo vietos *j* iki kelio sekcijos *r*, yra k_{jr}. *E* yra tiekimas prieš darbų pradžią (t_0), išreikštas dienomis. S_j yra saugus atsargų lygis perkrovimo vietoje *j*, išreikštas pilnais sunkvežimiais, ir L_j reiškia maksimalius perkrovimo vietos *j* pajėgumus. Kintamasis, kuris parodo medžiagų, pristatytų iš tiekėjo *i* į perkrovimo vietą *j* , kiekį x_{ij}, yra ne mažesnis,

nei 0 kiekvienam tiekėjui, kiekvienoje perkrovimo vietoje. Dvejetainis kintamasis, naudotas priskirti perkrovimo vietas konkrečioms kelio sekcijoms, y_{jr}, yra lygus 1, jei medžiagos, sekcijai *r* bus paimtos iš perkrovimo vietos *j* ir 0 kitu atveju. Galiausiai, $u_{ij\delta}$ egzistuoja dvejetainis kintamasis, kuris yra lygus 1 jei δ dieną medžiagos yra pristatomos iš tiekėjo *i* į perkrovimo vietą *j*, δ =-*E*+1, -*E*+2, ..., 0, 1, t_p.

Manoma, kad medžiagos konkrečiai kelio sekcijai gali būti gaunamos iš tos pačios perkrovimo vietos. Iš tiekėjo *i* pristatytų medžiagų, kiekis į iškrovimo vietą *j*, yra suma visų kasdieninių pristatymų nuo *i* iki *j* ir kiekviena perkrovimo vieta *j* gauna tiek, kiek reikia kelio sekcijai. Tiekėjų gamybos ir transportavimo pajėgumai yra riboti, todėl, kurią nors konkrečią dieną tiekėjas negali pateikti savo maksimalaus kasdieninio pristatymo į daugiau, nei į vieną perkrovimo vietą. Prekių kiekis perkrovimo vietoje negali būti didesnis už perkrovimo vietos pajėgumus ir negali pasidaryti mažesnis už saugų lygį. Vadinasi, tikslo funkcija yra:

$$\min z:\ z=\sum_{i=1}^{n}\sum_{j=1}^{m}c_{ij}\cdot x_{ij}+\sum_{j=1}^{m}\sum_{r=1}^{p}k_{jr}\cdot y_{jr}\cdot z_r\left(t_r-t_{r-1}\right)$$

Modelis gali atsižvelgti į mažesnius pristatymus (t. y. pateikiant mažiau už maksimalų kasdieninį vienetų skaičių nuo šaltinio iki paskyrimo vietos), bet todėl, kad kintamųjų ir apribojimų skaičius yra didelis, o aprašytas modelis yra iš tiesų pakankamai sudėtingas, būtina sukurti tam skirtus euristinius arba metaeuristinius algoritmus, kad būtų galima panaudoti jį taikant praktiškai. Tokiu būdu, įvedamos supaprastintos prielaidos. Pristatymai į perkrovimo vietas yra nepertraukiami nuo perkrovimo vietos paskyrimo momento. Pasirinkus, kas tieks į konkrečias perkrovimo vietas, (išsprendus *Modelį II*), pristatymų grafikai į perkrovimo vietas turėtų būti paruošti atskirai – panaudojant „klasikinius“ atsargų valdymo modelius, norint optimizuoti logistikos kaštus. Supaprastinto *Modelio II* tikslo funkcija turi tokią formą:

$$\min z:\ z=\sum_{i=1}^{n}\sum_{j=1}^{m}c_{ij}\cdot x_{ij}+\sum_{j=1}^{m}\sum_{r=1}^{p}k_{jr}\cdot y_{jr}\cdot z_r\left(t_r-t_{r-1}\right)+\sum_{j=1}^{m}\rho_j\cdot\left(v_j-T_j-D\right)$$

kur ρ_j reiškia kasdienius perkrovimo vietos *j* išlaikymo kaštus, arba yra pakankamai maži skaičiai, *D* yra medžiagų pristatymo į perkrovimo vietas dienų skaičius prieš pradedant darbus kelio sekcijose, kurias aptarnaus tos perkrovimo vietos, g_{ij} yra bendras kintamasis, ne mažesnis už 0, kuris reiškia skaičių dienų, kuriomis pristatomos medžiagos iš tiekėjo *i* į perkrovimo vietą *j*, T_j yra kintamasis, kuris reiškia perkrovimo vietos *j* atidarymo datą, o v_j reiškia perkrovimo vietos *j* uždarymo tiekimams datą. Galimybė pradėti pristatymus į *j* atsiranda ne vėliau, kaip *D* dienų, nuo darbų pradžios kelio sekcijose, kurias aptarnauja ši perkrovimo vieta. Laikantis prielaidos, kad pristatymai yra nepertraukiami, ši data yra ne vėliau kaip *D* dieną, prieš užbaigiant darbus ankstesnėse sekcijose, kurias aptarnauja ankstesnės perkrovimo vietos. Perkrovimo vietos veiklos laikas negali būti trumpesnis už pristatymų iš tiekėjų, aptarnaujančių tą vietą, priėmimo laiką. Buvo laikomasi prielaidos, kad kiekvienas tiekėjas pradeda tiekimą, kai tik atsidaro perkrovimo vieta. Vadinasi, jei tiekėjas aptarnauja kelias perkrovimo vietas, tiekimo pabaigos, į konkrečią perkrovimo vietą data turėtų būti ankstesnė už tiekimo į kitą, perkrovimo vietą, pradžią. Todėl tiekėjo pajėgumai nebus viršyti ir nebus medžiagų trūkumo. Esant iš dalies mažiems, kasdieniams perkrovimo vietos išlaikymo kaštams, tai palengvina pigiausių tiekėjų pasirinkimą. Tikslesni grafikai konkrečioms perkrovimo vietoms, gali būti optimizuoti po to, kai pasirenkama, kuris tiekėjas tieks, kokius kiekius ir į kurias perkrovimo vietas.

Sudėtinės logistikos grandinės, susietos su būtinybe rasti daug tiekėjų dideliems projektams ir rinkos skatinama ekonomiškumo paieška, gerinant organizaciją, neišvengiamai turės įtaką tokiems procesams. Matematinės optimizavimo priemonės bus taikomos praktikoje. Straipsnyje pateikti modeliai yra pavyzdys to, ką galima padaryti, panaudojant tokias priemones, kurios yra tik truputį sudėtingesnės už įprastines skaičiuokles.

Raktažodžiai: *pervežimo problema, tiekimo grandinės valdymas, kelio tiesimas, grafiko apribojimai*.

The article has been reviewed.

Received in February, 2013; accepted in February, 2014.