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Methods of planning deliveries of food products to a trade network with the selection of suppliers and transport companies

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The paper refers to planning deliveries of food products (especially those available in certain seasons) to the recipients: supermarket networks. The paper presents two approaches to solving problems of simultaneous selection of suppliers and transportation modes and construction of product flow schedules with these transportation modes. Linear mathematical models have been built for the presented solution approaches. The cost criterion has been taken into consideration in them. The following costs have been taken into account: purchase of products by individual recipients, transport services, storing of products supplied before the planned deadlines and penalties for delays in supply of products. Two solution approaches (used for transportation planning and selection of suppliers and selection of transportation modes) have been compared. The monolithic approach calls for simultaneous solutions for the problems of supplier selection and selection of transportation modes. In the alternative (hierarchical) solution approach, suppliers are selected first, and then transportation companies and their relevant transportation modes are selected. The results of computational experiments are used for comparison of the hierarchical and monolithic solution approaches.

Key words: supply network, supply chain management, logistics, integer programming, transportation, scheduling, hierarchical planning

1. Introduction

A certain trade company has a network of trade facilities in which food products are sold. Fruits and vegetables constitute a substantial part of these products. These are seasonal products, many of them features short expiry dates. Due to the seasonal market of these products, new suppliers of products are sought from time to time. The company cares about delivering fresh products to its trade facilities, within a short time, directly from producers. For the purpose of deliveries of these products, the trade company takes advantage of the services of transport companies which have various transportation modes suitable for transporting

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food products. The trade company monitors the market of services and does its best to cooperate with such suppliers of products and tried companies that offer favourable conditions, especially in the scope of prices of the offered services. The issues related to managing the market of fresh food, transported between links of supply chains, was described by Nakadala *et al.* (2017).

In order to plan deliveries of food products to the facilities of the trade company, the mathematical models of discrete optimization tasks developed by the author of this article were used. The monolithic method has been built which can be used to simultaneously define the schedule of product deliveries, as well as to select suppliers and transport companies and their means of transport. In case of problems of relatively significant sizes, the hierarchical method is proposed. First, selection of suppliers is done, and then selection of transport companies occurs and the schedule of product deliveries is defined. Both methods were compared with the conducted computational experiments.

The issues included in the paper applies thus to a supply network. Control over flow of products through supply networks is a concept in management of relationships between suppliers and recipients aimed at delivering products at the lowest possible costs of maintenance of supply networks. It includes integrated processes of planning, procurement, production, shipments and returns, along with flow of information, materials and work (Stadtler, 2005).

The mathematical models presented in the paper are used, among others, for scheduling transportation tasks. Integer programming has been used for this purpose. Application of this mathematical tool for task scheduling for supply networks was inspired with the works of Osman and Demirlia (2010), Sawik (2010), Geiβler *et al.* (2011), Zhang and Zhang (2011). These works show that integer programming may be used not only for task scheduling for supply networks, but also for designing these networks, which is the subject matter of this paper. The possibility of finding optimum solutions for many problems (obviously enough, in terms of the criteria taken into account) is a clear advantage of discrete optimization. The problem of scheduling for supply networks is the subject of intensive research, the researchers are connected with consideration of multimodal transport, among others (Bocewicz *et al.*, 2017).

The mathematical models described in this paper are based on a transport task formulated for transferring products between suppliers and recipients (Stadtler *et al.*, 2015). The classic transport task has been expanded here and many various types of products, different transportation companies and their transportation modes have been taken into account, along with many parameters which describe the products and the possibilities of the transportation modes.

The mathematical models have been developed for short-term planning of product flow between suppliers and recipients which constitute links in supply networks. This resulted from the limited possibilities of the available discrete optimization packages.

The mathematical models presented in this paper are used for transportation planning between links in the supply network. SteadieSeifi *et al.* (2014) prepared a review of literature dedicated to transportation planning with various transportation modes. Their paper presents a structural overview of the multimodal transportation literature from 2005. The traditional strategic, tactical, and operational levels of transportation planning are described. The routing problem is related to the stated issues. The paper prepared by Bertazzi and Speranza (2012) describes the inventory routing problems, and presents different models and policies for the class of the problems. This paper also contains an rich overview of the papers connected with the inventory routing problems.

The developed mathematical models are used not only for planning product flow through supply networks, but also for elements of designing networks. Two basic problems are solved which are related to designing this flow structure: selection of suppliers and selection of transportation companies.

The paper prepared by Dullaert *et al.* (2007) reviews the literature on supply chain design since 1999. The issues of designing supply networks, including an overview of publications from the recent years is given and in Chapter 3 of the book written by Chandra and Grabis (2007), and in Sawik (2011b). However, attention should be paid to the fact that designing supply chains (including those of network nature) refers mostly to long time horizons. The review of the literature on mathematical models built for designing supply chains was prepared by Lambiase *et al.* (2013).

For effective control over flow of products through supply networks, selection of the appropriate suppliers, transportation companies and their transportation modes are of crucial importance. The structure of supply networks may often be modified, following the needs of recipients. Designing supply networks should take into consideration a number of factors which affect control over product flow through these networks.

A number of factors are taken into account at the same time in selection of suppliers, including: costs of products, transport; delivery time; reliability, or proper execution of the order and penalties for late deliveries; communication understood as a form of dialogue with the supplier; willingness of the supplier to meet additional requirements (Osman and Demirli, 2010). The nature of multifactorial supplier selection process is referred to us MAGDM – Multi-attribute Group Decision Making (Samantra et al., 2012).

Selection of suppliers results in selection of transportation companies. Selection of transportation companies takes into consideration, among others, the following factors: availability of various transportation modes and their immunity to disturbances; duration of the transport process; ensuring the appropriate shipment documentation; organization and execution of storage services; sanitary supervision and customs clearance (if any). All these factors have bearing on the amount of the costs incurred, which are one of the most important factors viewed in selection. At present, many companies strive to present as many advantages as they can. For example, many transportation companies, apart from their basic services, provide also additional services. These are logistics operators. Many suppliers, in order to gain advantage over other companies, offers their own transport. Experience in the past is also important in selection of business contractors.

Additional, significant factors which are taken into account in selection of suppliers or transportation companies and are often omitted include environmental factors. The weight of these factors has been emphasised in Rigo *et al.* (2007). The analysis of the incurred costs related to transport of products between chain links often contributes to omitting environmental factors. Omitting these factors results in, among others, environmental pollution or unwanted noise. Preliminary selection of suppliers and transportation modes and elimination of solutions least favourable for the environment may be the solution to this problem. Obviously enough, it may result in the necessity of increasing costs related to operation of a supply network.

Due to its structure, the necessity of transporting products, often for long distances, supply networks constitute a specific group of production systems. The issues of modelling supply chains, including those of network nature, was broadly studied by, among others, Agnetis and Hall (2006), Sawik (2011a). The analysis of studies dedicated to these issues shows a major advantage of application of cost criteria in building schedules of product flow for supply networks. In many studies, significant costs are omitted, including costs of storing or penalties for delayed deliveries. Ghodsypour and O'Brien (2001) have taken into account a number of costs related to support for supply networks in the developed mathematical models, including not only costs of product purchase and transport, but also the costs incurred due to delayed deliveries. The analysis of costs related to functioning of logistic networks is also given in Janic (2009). These costs have also been taken into account in the mathematical models presented in this paper. Unlike with non-linear models proposed by Ghodsypour and O'Brien (2001), the models presented in this paper are linear and are also dedicated for scheduling transport tasks.

The authors of the paper, Gheidar Kheljani *et al.* (2009), have reported a known, but very important problem, related to optimization of costs. The methods used for optimization of costs in the scale of a supply network take into consideration the interests of the whole. The interests of individual production plants (network links) may be different from and contrary to the interest of the whole.

An overview of the literature related to multi-criteria supplier selection for supply chains has been prepared by Ho, Xu and Dey (2010). A major part of multi-criteria methods is based on selection of weights for the relevant criteria, as with, for example, the AHP method (Analytic Hierarchy Process, Satty, 1980). The solution approaches (hierarchical and monolithic) prepared in this paper refer to this concept. The proposed approach to supplier and transportation companies selection includes application of the AHP method for initial supplier and selection of transportation modes. It is aimed at reducing a large volume of data in the tasks for supplier selection and selection of transportation modes which are solved next and which take into account the cost criterion.

In the summary and general characteristics of the solution approaches based on integer programming in this paper, one can state that they are used not only for supplier selection, but also for selection of transportation companies and transportation modes. Solving the tasks related to network designing is done with the simultaneous construction of schedules of product flow through these networks.

As the issues of efficient and economically effective process of product flow planning are taken into consideration, the developed solution approaches are related to production logistics and transport logistics. Mathematical programming used in these solution approaches is, on the other hand, part of operational research.

The concepts on which the developed solution approaches are based have been described in section 2. Section 3 is dedicated to presentation of linear mathematical models built for these solution approaches. Section 4 includes the results of calculation experiments dedicated to verification of the mathematical models built for monolithic and hierarchical solution approaches.

2. Hierarchical and monolithic solution approaches

The approaches for controlling flow of products have been developed for supply chains of network nature. It means parallel support for multiple suppliers and multiple recipients. A sample structure is presented in Fig. 1. The concepts refer to designing and building relationships between consecutive groups of links: suppliers and recipients – producers of goods (Macchian *et al.*, 2017). Recipients, who buy products (components), usually become also suppliers of products for further links in the networks.

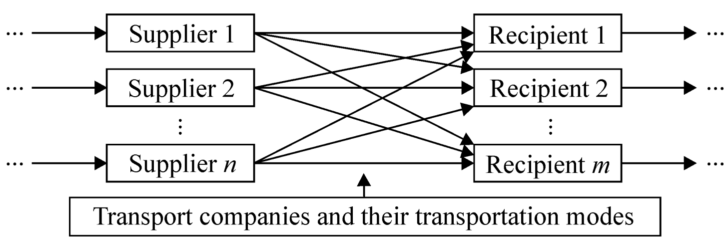

Figure 1: Example of fragment of supply network structure

Selections of suppliers and transportation modes are made based on one of two solution approaches: monolithic or hierarchical. These concepts are visualised on flowcharts in Fig. 2. The first of these concepts (hierarchical) consists of two levels. Solving the problem of selecting transportation companies and transportation modes is preceded with selection of suppliers. In the alternative approach (monolithic, one-level), both these problems are solved simultaneously (Magiera, 2016). The hierarchical solution approach has been widely studied by Miller (2002), Schneeweiss and Zimmer (2004). The paper by Miller (2002) presents understanding of how hierarchical planning techniques can contribute to the effective management and planning of supply chain activities. The advantages resulting from application of the hierarchical solution approach in controlling product flow through supply chains are described by Schneeweiss and Zimmer (2004).

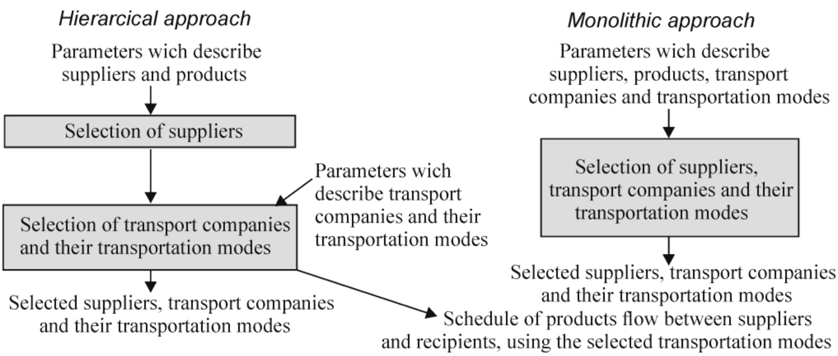

Figure 2: Concepts of the two solution approaches: hierarchical and monolithic

The advantage of the monolithic approach is its global view of the problem, thus making the obtained results more advantageous than in splitting a task into sub-problems. In case of the multilayer approach, solving the tasks from the lower level is dependent on the results from the previously solved problem. The monolithic approach to selection of suppliers and transportation modes requires, however, simultaneous considering of many parameters, variables, constraints. This concept may be thus used for solving problems of relatively small size. Using the multilayer approach is recommended for solving problems of relatively large size.

3. Mathematical models

The block diagrams in Fig. 1 apply also for the described solution approaches prepared by the author of the paper. For both solution approaches (hierarchical and monolithic), linear mathematical models were built. The cost criterion was taken into consideration in them. Table 1 presents markings for the solution approaches and for the mathematical models.

Table 1: Markings for the solution approaches and mathematical models

Solution approach	Markings for the models and their description
H – hierarchical	P1 – formulated for the level I – selection of suppliers P2 – formulated for the level II – selection of transportation companies and their transportation modes
M – monolithic	P3 – selection of suppliers, transportation companies and their transportation modes

The input data are parameters which describe suppliers, products, transportation companies and transportation modes. In order to limit the volume of the data, pre-selection of suppliers and transportation companies is recommended. The multi-criteria AHP method (*Analytic Hierarchy Process*) is suggested for this purpose. This method is described, among others, by Saaty (1980) – the author of this method.

The AHP method may take into account the factors which affect assessment of suppliers and transportation companies, referred to in the introduction. The next stage takes into account several suppliers and transportation companies which ranked best. As a result of this limitation of the numbers of parameters and variables, the problems formulated in the linear mathematical models are smaller.

The summary of indices used in the mathematical models built for the approaches (H and M) are given in Table 2.

Table 2: Summary of indices used in the mathematical models

Indices:		l – time interval (period); $l \in L$;
	i – supplier; $i \in I$;	n – order; $n \in N$;
	j – recipient; $j \in J$;	s – transportation mode; $s \in S$;
	k – product; $k \in K$;	f – transportation company; $f \in F$;

Due to the two approaches to the solution of the problem, no list of common parameters may be decided upon. In case of the hierarchical solution approach, some parameters for the problem solved on a lower level are the solutions of the higher-level problems. The parameters used in mathematical models constructed for the both solution approaches are stated in Table 3.

The mathematical description of the problem shows that there may be various approaches to formulation of a large number of parameters and constraints.

Table 3: Summary of markings for parameters and sets used in the models built for the mathematical models constructed for the H and M approaches

a_{ij}	–	minimum sum of prices of ordered products by recipient j from supplier i, which gives right to discount;
b_{fj}	–	minimum sum of prices of transport service executed by transportation company f for recipient j, which gives right to discount;
c^1_{ik}	–	price of pallet of product k, sold by supplier i (without discount);
c^2_{ij}	–	amount of discount offered by supplier i to recipient j due to the determined costs of purchase of products, that is at least a_{ij};
c^3_{ij}	–	cost of one-time use of a transportation modes between supplier i and recipient j (without discount);
c^4_{sl}	–	cost index for transportation mode s during period l, with the possibility of differentiating fixed costs in particular periods;
c^5_{sk}	–	cost of using transportation mode s in reference to transporting pallet of product k (cost of loading, unloading);
c^6_{jk}	–	penalty for each period of delay in delivery of pallet of product k to supplier j;
c^7_{jk}	–	cost of storing the prematurely provided pallet of product k with supplier j, incurred within the unit of time;
c^8_{fj}	–	amount of discount offered by transportation company f to recipient j due to the determined costs of service, that is at least b_{fj};
d_{ikl}	–	number of pallets of products k available in period l from supplier i (supply);
g_{sl}	–	1, if transportation mode s is available during period l, otherwise $g_{sl} = 0$;
m^1_k	–	weight of pallet of product k along with its package;
m^2_s	–	load capacity of transportation mode s;
o^1_j	–	maximum number of suppliers supporting recipient j;
o^2_j	–	maximum number of transportation companies supporting recipient j;
t_{sij}	–	transportation time using transportation mode s between supplier i and recipient j;
$t_{\min n}$	–	period (the time range) within which the activities related to transport and aimed at execution of order n may be first started;
$t_{\max n}$	–	planned date of execution of order n;
v^1_k	–	loading space taken by pallet of product k;
v^2_s	–	loading space of transportation mode s;
P	–	the set of pairs (f,s), where the transportation mode s is connected with the transportation company f;
α	–	any integer larger than the number of the considered periods l;
β	–	any integer larger than demand for any pallet of product k by any recipient j (the maximum demand).

In case of the monolithic solution approach, the orders are given: demands for various types of products which are to be delivered at the same time are known in the given period of time. In case of the hierarchical solution approach, demands for products in various periods of time are known. The breakdown into orders and batches of products of various types which are to be shipped at the same time with one transportation mode is done at the first level of the solution approach. It requires different defining of not only some parameters but also variables.

3.1. Mathematical models for the hierarchical solution approach (H)

Level I: selection of suppliers

After the initial selection of the suppliers, aimed at, among others, reduction of the volume of data, the discrete optimization problem is solved, as formulated in the linear mathematical model. The parameters and variables adopted for the solution of the selection of suppliers problem are given in Table 4. The other markings correspond with Table 3.

Table 4: Summary of parameters and variables adopted for the problem of supplier selection (the approach H)

Input parameters:		
c^9_{ijl}	–	estimated minimum price of the transport service between plants i, j executed within the time l;
p_{jkl}	–	volume of demand in plant j for the pallet of products k during the period l;
A	–	the set of pairs (j,k), in which recipient j has demand for products k;
R	–	the set of three elements (j,k,l), in which recipient j has demand for products k in period l;
T	–	the set of three elements (i,j,l), where transport of products between supplier i and recipient j is possible during the period l;
W	–	the set of three elements (i,k,l), in which producer i has products k available for transport during period l.
Variables:		
r_{jkl}	–	number of pallets of products k in surplus with recipient j during period l;
w_{jkl}	–	number of missing pallets of products k with recipient j during period l;
x_{ijkl}	–	number of pallets of products k transported during period l between plants of producers: i, j (i – supplier, j – recipient);
y_{ij}	–	1, if supplier i delivers products to recipient j, otherwise $y_{ij} = 0$;
z_{ijl}	–	1, if during period l transport is executed between supplier i and recipient j, otherwise $z_{ijl} = 0$;
ρ_{ij}	–	1, if supplier i grants discount to recipient j, otherwise $\rho_{ij} = 0$.

A group of decision variables may be determined in all the presented mathematical models. In case of the following mathematical model, variables y_{ij} belong to the group of these variables (Table 4). On the basis of the value of these variables, known after application of the P1 model, a list of suppliers i is built who support individual recipients. The suppliers i, for whom $y_{ij} = 0$, are not taken into consideration at the lower level of the proposed hierarchical solution approach. Variables informing about awarding discounts also belong to this group of variables. In case of the P1 model, variables ρ_{ij} were defined, informing about the decision on granting discounts by individual suppliers i to the given recipients j – discounts are granted in case of ordering products by recipients j from suppliers i, whose cost of purchase is at least a_{ij} (Table 3). The parameters presenting the amounts of the granted discounts are described in Table 3.

Integer variables constitute the second group of variables. They are used, among others, to determine the number of individual types of products transported with the given routes, that is between suppliers and recipients. In case of the model P1, variables x_{ijkl} were defined, with which the route between the delivery i and the recipient j is assigned the number of pieces of the products k transported during the period l. Attention should be also paid to define variables used to reflect delayed deliveries. These include the variables which define deficiencies in the individual products in the particular periods of time (the variables w_{jkl} – Table 4). They are the basis for assigning penalties for delays in delivering products. The variables (r_{jkl}) were also set which inform about early deliveries of products in the particular periods of time. Storing costs are incurred in case of deliveries of products before the ordered date of their delivery.

The relations between the described variables and parameters are taken into account in the following mathematical model.

The **P1 model**, formulated for the supplier selection problem, for the solution approach H:
Minimize:

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{l\in L} c^1_{ik}x_{ijkl} - \sum_{i\in I}\sum_{j\in J} c^2_{ij}\rho_{ij} + \sum_{(i,j,l)\in T} c^9_{ijl}z_{ijl} + \sum_{(j,k)\in A}\sum_{l\in L}\left(c^6_{jk}w_{jkl} + c^7_{jk}r_{jkl}\right) \tag{1}$$

subject to:

$$\sum_{i\in I}\sum_{l\in L:(i,j,l)\in T} x_{ijkl} = \sum_{l\in L:(j,k,l)\in R} p_{jkl}; \quad j\in J; \quad k\in K, \tag{2}$$

$$\sum_{l\in L}\sum_{k\in K:(j,k,l)\in R} c^1_{ik}x_{ijkl} \geqslant a_{ij}\rho_{ij}; \quad i\in I; \quad j\in J, \tag{3}$$

$$x_{ijkl} \leqslant \beta y_{ij}; \quad i \in I; \quad j \in J; \quad k \in K; \quad l \in L, \tag{4}$$

$$\sum_{i \in I} y_{ij} \leqslant o_j^1; \quad j \in J, \tag{5}$$

$$\sum_{j \in J} x_{ijkl} \leqslant \sum_{\tau \in L:\, \tau \leqslant l \wedge (i,k,\tau) \in W} d_{ik\tau}; \quad i \in I; \quad k \in K; \quad l \in L, \tag{6}$$

$$\sum_{k \in K} x_{ijkl} \leqslant \beta z_{ijl}; \quad i \in I; \quad j \in J; \quad l \in L, \tag{7}$$

$$\sum_{\tau \in L: \tau \leqslant l} \sum_{i \in I} x_{ijk\tau} - \sum_{\tau \in l: \tau \leqslant l \wedge (j,k,\tau) \in R} p_{jk\tau} \leqslant r_{jkl}; \quad j \in J; \quad k \in K; \quad l \in L, \tag{8}$$

$$\sum_{\tau \in L: \tau \leqslant l \wedge (j,k,\tau) \in R} p^1_{jk\tau} - \sum_{\tau \in l: \tau \leqslant l} \sum_{i \in I} x_{ijk\tau} \leqslant w_{jkl}; \quad j \in J; \quad k \in K; \quad l \in L, \tag{9}$$

$$\rho_{ij},\ y_{ij},\ z_{ijl} \in \{0, 1\}; \quad i \in I; \quad j \in J; \quad k \in K; \quad l \in L,$$
$$r_{jkl},\ w_{jkl},\ x_{ijkl} \geqslant 0, \text{ integer}; \quad i \in I; \quad j \in J; \quad k \in K; \quad l \in L. \tag{10}$$

The minimized sum (1) represents the costs of: purchase of products (including discounts for purchases of a pre-defined number of pieces of these products), transport, related to delayed delivery of the products – costs of storing and penalties for any contractual period of delay in the delivery of the product. The stated costs of transport of products are estimated. Location of the plants of the suppliers is important, as it affects the costs of delivering semi-finished products. The costs of transport, including parameters of the transportation modes and discounts for transport services offered by the selected companies are included at the lower level of the solution approach, in the problem of selection of transportation companies and transportation modes.

The constraints built for the described mathematical model ensure: (2) – delivery of the required number of particular products to every single recipient; (3) – granting discounts for ordering the relevant number of pieces of the products; (4) – determining the list of suppliers of the products; (5) – reducing the number of suppliers of the products; (6) – including availability of particular products in the specific periods with the given suppliers; (7) – determining demand for the use of transportation modes between the suppliers and the recipients in specific periods of time; (8) – determining surpluses of products with the recipients in particular periods of time; (9) – determining shortages of components with the recipients in particular periods of time; (10) – the relevant types of variables.

The constraint (5), restricting the number of suppliers, may be omitted. This model may be used for simulations: verifying the number of suppliers against deadlines for deliveries and the resulting costs. Increasing the number of suppliers results in the reduction of discounts obtained for ordering the specified number of pieces of the products, though.

Level II: selection of transportation companies and their transportation modes

Demand for transport of specific volumes of products determined for particular periods of time constitute input data for the second level of the solution approach. The determined values of variables become parameters for the next problem to be solved.

The analysis of the value of the variables y_{ij} (Table 4) make known the list of suppliers $i \in I$, with whom the recipients $j \in J$ ordered products of various types. To obtain full information used to connect supply and demand, the values of the variables x_{ijkl} should be read (Table 4). The values of these variables inform about the number of products of type k which should be transported between the supplier $i \in I$ and the recipient $j \in J$ in the given period of time $l \in L$. On the basis of the value of the stated variables, the sets D are defined (Table 5, for the lower

Table 5: Input parameters and variables for the second level of the approach H

Input parameters and sets:		
c^{10}_{ijs}	–	cost of using the transportation mode s for transport between supplier i and recipient j;
c^{11}_{nk}	–	penalty for each period of delay of pallet of products k in execution of order n;
c^{12}_{nk}	–	cost of storing the prematurely provided pallet of products k in execution of order n, incurred within the unit time;
h_{sk}	–	1, if transportation mode s is suitable to transport product k, otherwise $h_{sk} = 0$;
p_{nk}	–	number of pallets of products k included in order n;
D	–	the set of three elements (n, i, j), in which order n is connected with using transportation modes between supplier i and recipient j;
Variables:		
q_{fj}	–	1, if transportation company f supports recipient j, otherwise $q_{fj} = 0$;
r_{nskl}	–	number of pallets of product k in surplus during period l for execution of order n, using transportation mode s (the products are supported before the planned date of execution of order n);
u_{ns}	–	1, if transportation mode s is selected for execution of order n, otherwise $u_{ns} = 0$;
w_{nskl}	–	number of missing pallets of product k during period l in execution of order n, using transportation mode s.
x_{nks}	–	numbers of pallets of products k supported using the transportation mode s for execution of order n;
z_{nsl}	–	1, if during period l transport of products is done with the transportation mode s to execute order n, otherwise $z_{nsl} = 0$;
v_{fj}	–	1, if transportation company f grants discount to recipient j, otherwise $v_{fj} = 0$;

level) of the ordered sets of three variables (n,i,j), where the order n includes a transport of products between the supplier i and the recipient j. All the products assigned to the given order (known on the basis of the values x_{ijkl}) are transported at the same time. The demand for transport of various types of products between the same suppliers and recipients, determined with the variables x_{ijkl}, which is to take place in the same period of time, may be assigned to one order. p_{nk} is the parameter which informs about the number of products k assigned to the order n, stated in Table 5.

Table 5 presents all parameters and variables for the second level of the solution approach: selection of transportation companies and their transportation modes and construction of the product flow schedule between the links in the supply network.

It has to be noted that the majority of parameters and variables presented in Table 5 are assigned with the order index n, which may be interpreted as the number of the order. For each order, the transportation mode and the period in which the transport will take place (z_{nsl}) are assigned. Too early or too late deliveries of products (against the given date of execution of the order n) are recorded with the variables r_{nskl} and w_{nskl}. After determination of the value of these variables for each period l, the numbers of surplus products (products delivered too early) and deficiencies (products delivered too late) of the individual products k are known. These variables are taken into account in the minimized sum (11), corresponding with the following mathematical model.

The **P2 model**, formulated for selection of companies and transportation modes – for the approach H:
Minimize:

$$\sum_{(n,i,j)\in D}\sum_{s\in S}\sum_{l\in L} c^{10}_{ijs} c^{4}_{sl} \frac{z_{nsl}}{t_{sij}} + \sum_{n\in N}\sum_{k\in K}\sum_{s\in S}\left[c^{5}_{sk} x_{nks} + \sum_{l\in L}\left(c^{11}_{nk} w_{nskl} + c^{12}_{nk} r_{nskl}\right)\right] - \sum_{f\in F}\sum_{j\in J} c^{8}_{fj} v_{fj}\,, \tag{11}$$

subject to:

$$\sum_{l\in L, g_{sl}=1} z_{nsl} \geqslant t_{sij} u_{ns}; \quad (n,i,j)\in D; \quad s\in S, \tag{12}$$

$$\sum_{s\in S} x_{nks} = p_{nk}; \quad k\in K; \quad n\in N, \tag{13}$$

$$x_{nks} \leqslant \beta h_{sk} u_{ns}; \quad k\in K; \quad n\in N; \quad s\in S, \tag{14}$$

$$q_{fj} \geqslant u_{ns}; \quad (f,s)\in P; \quad (n,i,j)\in D, \tag{15}$$

$$\sum_{f\in F} q_{fj} \leqslant o_j^2; \quad j\in J, \tag{16}$$

$$\sum_{k\in K} v_k^1 x_{nks} \leqslant v_s^2; \quad n\in N; \quad s\in S, \tag{17}$$

$$\sum_{k\in K} m_k^1 x_{nks} \leqslant m_s^2; \quad n\in N; \quad s\in S, \tag{18}$$

$$l z_{nsl} - \tau z_{ns\tau} \leqslant t_{sij} - 1 + \alpha(1 - z_{ns\tau}); \quad (n,i,j)\in D; \quad \tau, l\in L; \quad \tau < l, \tag{19}$$

$$\sum_{n\in N} z_{nsl} \leqslant g_{sl}; \quad l\in L; \quad s\in S, \tag{20}$$

$$l z_{nsl} \geqslant t_{\min n} - \alpha(1 - z_{nsl}); \quad l\in L; \quad n\in N; \quad s\in S, \tag{21}$$

$$l z_{\mu sl} - \tau z_{ns\tau} \geqslant u_{\mu s}(t_{s\varepsilon j}+1) - \alpha(2 - z_{ns\tau} - z_{\mu sl});$$

$$\tau, l\in L; \quad l > \tau, \quad (n,i,j),\,(\mu,\varepsilon,\kappa)\in D; \quad n\neq\mu; \quad s\in S, \tag{22}$$

$$\sum_{(n,i,j)\in D}\ \sum_{s\in S:(f,s)\in P} c_{ijs}^1 c_{sl}^2 \frac{z_{nsl}}{t_{sij}} + \sum_{n\in N}\sum_{k\in K}\ \sum_{s\in S,(f,s)\in P} c_{sk}^5 x_{nks} \geqslant b_{fj}^2 \nu_{fj};$$

$$j\in J; \quad f\in F, \tag{23}$$

$$w_{nskl} \geqslant x_{nks} - \beta(1 - z_{nsl});\ \ k\in K;\ \ s\in S;\ \ l\in L;\ \ l > t_{\max n}+1;\ \ g_{sl}=1, \tag{24}$$

$$w_{nskl} \leqslant w_{nsk\,l-1};\ \ k\in K;\ \ s\in S;\ \ l\in L;\ \ l > t_{\max n}+1;\ \ g_{sl}=1;\ \ p_{nk}>0, \tag{25}$$

$$r_{nskl} \geqslant x_{nks} - \alpha(1 - z_{ns\,l-t_{sij}+1});$$

$$k\in K,\ s\in S,\ \ (n,i,j)\in D;\ \ l\in L;\ \ l < t_{\max n};\ \ l\geqslant t_{sij};\ \ g_{sl}=1;\ \ p_{nk}>0, \tag{26}$$

$$r_{nsk\,l+1} \geqslant r_{nskl};\ \ k\in K;\ \ s\in S;\ \ l\in L;\ \ l < t_{\max n}-1;\ \ g_{sl}=1;\ \ p_{nk}>0, \tag{27}$$

$$u_{ns}, z_{nks}\in\{0,1\};\ \ n\in N;\ \ k\in K;\ \ s\in S;\ \ \nu_{fj},\ q_{fj}\in\{0,1\};\ \ f\in F;\ j\in J, \tag{28}$$

$$r_{nskl},\ w_{nskl},\ x_{nks}\geqslant 0, \quad \text{integer},\ \ k\in K;\ \ l\in L;\ \ n\in N;\ \ s\in S. \tag{29}$$

The minimized sum (11) includes costs of execution of individual transport orders. They depend on the type of the selected transportation modes and the number of the transported pallets of products. Discounts, costs of storing products shipped early and penalties for each period of delay in shipment of individual products have also been taken into account. Further constraints guarantee: (12) – execution of all transport activities (including travel times); (13) – allocation of all pallets of products for the transportation modes; (14) – assignment of the transportation modes to particular orders; (15) – determining the list of transportation companies which support individual recipients; (16) – reducing the number of transportation companies which supporting individual recipients; (17) – verification of the loading space for each transportation mode (securing place for individual products); (18) – verification of load capacity for individual transportation modes; (19) – continuity of execution of transportation activities assigned to the given order, executed with the selected transportation mode: in the case when the transport duration includes several periods of time, transportation tasks are executed in the following, directly successive periods of time; (20) – handling at the most one order by the transportation mode at the given time (during period l); (21) – starting execution of transport activities only after the products are prepared; (22) – determining the minimum breaks between consecutive travels in order to set aside time for travel to the suppliers; (23) – assigning discounts (making decision) to the recipients by particular transportation companies; (24), (25) – determining the number of pallets of missing products (shortages) in specific periods of time; (26), (27) – determining the pallets of products which must be stored in specific periods of time; (28), (29) – the relevant types of variables.

As with the problem analysed at the upper level (the problem of supplier selection), the restriction (16) may be skipped (the restriction on the number of transportation companies which support recipients). Increasing the number of transportation companies may improve timely deliveries, which is clearly affecting the costs related to transport tasks (reduction of penalties and costs of storing, but also reduction of discounts and increase in the number of travels).

The result of applying the approach H is the schedule of deliveries of components from the selected suppliers to the principals with the selected companies and their transportation modes.

3.2. Mathematical models for the monolithic solution approach (M)

Table 6 presents parameters and variables used in the P3 model built for the monolithic approach. All other markings are consistent with those presented in Table 3.

The variables given in Table 6 refer to both the supplier selection problem (the variables y_{ni}, ρ_{ij}) as well as the transportation company selection problem (the variables q_{fj} and ν_{fj}) and the assigned transportation modes. Similarly, as in the case of the markings adopted for the model P2 (Table 5), the orders were formulated. Each order n is assigned the recipient j, known with E, a set of pairs (n, j). Each order is assigned the number of pallets of products k, which is to be transported to the recipient; the parameter p_{nk} is defined for this purpose in Table 5. For each order, the time of delivery of the products of the order is determined, marked e_n. When the order n is executed before the time limit set with the recip-

Table 6: Parameters and variables used in the P3 model

Parameters and sets:		
h_{sn}	–	1, if the transportation mode s is suitable for execution of the order n, otherwise $h_{sn} = 0$;
p_{nk}	–	number of pallets of products k covered by order n (demand);
E	–	the set of pairs (n, j), where order n includes recipient j;
Variables: u_{ns}		
e_n	–	period in which the products will be delivered which are covered by order n;
r_n	–	time (period) of the early execution of order n;
w_n	–	time (period) of delay in execution of order n;
q_{fj}	–	1, if transportation company f supports recipient j, otherwise $q_{fj} = 0$;
u_{ns}	–	1, if transportation mode s is selected for execution of order n, otherwise $u_{ns} = 0$;
x_{nisl}	–	1, if during period l transport of products is done using transportation mode s from supplier i to execute order n, otherwise $x_{nisl} = 0$;
y_{ni}	–	1, if supplier i is selected to execute order n, otherwise $y_{ni} = 0$;
ρ_{ij}	–	1, if supplier i grants discount to recipient j, otherwise $\rho_{ij} = 0$;
ν_{fj}	–	1, if transportation company f grants discount to recipient j, otherwise $\nu_{fj} = 0$;

ient of the products (the parameter $t_{\max n}$), the value of the variable r_n is the time of delivery of the products of the order, otherwise $r_n = 0$. When delay is in the execution of the order n, the value of the variable w_n represents the time of delivery of the products of this order, otherwise $w_n = 0$. The values of these variables are significant in determination of the costs related to delayed deliveries. Much information is encoded in the binary variables x_{nisl}: they show, among others, decisions (if $x_{nisl} = 1$) on the application of the transportation mode s during the period l to execute the order n – to transport products from the supplier i to the recipient assigned to the order n. The following is the mathematical model with the relations between the described parameters and variables.

The **P3 model** for the monolithic solution approach (M):
Minimize:

$$\sum_{i\in I}\sum_{k\in K}\sum_{n\in N} c^1_{ik} p_{nk} y_{ni} - \sum_{i\in I}\sum_{j\in J} c^2_{ij}\rho_{ij} + \sum_{i\in I}\sum_{l\in L}\sum_{s\in S}\sum_{(n,j)\in E} c^3_{sij} c^4_{sl}\frac{x_{nisl}}{t_{sij}}$$
$$+ \sum_{n\in N}\sum_{k\in K}\sum_{s\in S} p_{nk} c^5_{sk} u_{ns} - \sum_{f\in F}\sum_{j\in J} c^8_{fj}\nu_{fj} + \sum_{(n,j)\in E}\sum_{k\in K} p_{nk}\left(c^6_{jk} w_n + c^7_{jk} r_n\right), \quad (30)$$

subject to:

$$\sum_{i\in I} y_{ni} = 1; \quad n\in N, \tag{31}$$

$$\sum_{i\in I}\sum_{n\in N:(n,j)\in E} y_{ni} \leqslant o_j^1; \quad j\in J, \tag{32}$$

$$\sum_{n\in N}\sum_{s\in S} p_{nk}x_{nisl} \leqslant \sum_{\tau\in L:\tau\leqslant l} d_{ik\tau}; \quad i\in I; \quad k\in K; \quad l\in L, \tag{33}$$

$$\sum_{k\in K}\sum_{n\in N:(n,j)\in E} p_{nk}c_{ik}^1 y_{ni} \geqslant a_{ij}\rho_{ij}; \quad i\in I; \quad j\in J, \tag{34}$$

$$\sum_{s\in S:h_{sn}=1} u_{ns} = 1; \quad n\in N, \tag{35}$$

$$\sum_{j\in J:(n,j)\in E} q_{fj} \geqslant u_{ns}; \quad (f,s)\in P; \quad n\in N, \tag{36}$$

$$\sum_{f\in F} q_{fj} \leqslant o_{2j}; \quad j\in J, \tag{37}$$

$$\sum_{l\in L} x_{nisl} \geqslant t_{sij}u_{ns} - \alpha(1-y_{ni}); \quad i\in I; \quad s\in S; \quad (n,j)\in E, \tag{38}$$

$$\sum_{i\in I}\sum_{n\in N} x_{nisl} \leqslant g_{sl}; \quad l\in L; \quad s\in S, \tag{39}$$

$$lx_{nisl} - \tau x_{nis\tau} \leqslant (t_{sij}-1)u_{ns} + \alpha(1-x_{nis\tau});$$
$$(n,j)\in E; \quad i\in I; \quad s\in S; \quad l,\tau\in L; \quad \tau<l, \tag{40}$$

$$lx_{nisl} - \tau x_{\eta\varepsilon s\tau} \geqslant t_{si\upsilon} + 1 - \alpha(1-x_{\eta\varepsilon s\tau}) - \alpha(1-x_{nisl});$$
$$(\eta,\upsilon)\in E; \quad n\in N; \quad l,\tau\in L; \quad s\in S; \quad i,\varepsilon\in I; \quad n\neq\eta; \quad \tau<l, \tag{41}$$

$$e_n \geqslant lx_{nisl}; \quad i\in I; \quad l\in L; \quad n\in N; \quad s\in S, \tag{42}$$

$$e_n \leqslant lx_{nisl} + t_{sij} - 1 + \alpha(1-x_{nisl}); \quad (n,j)\in E; \quad i\in I; \quad l\in L; \quad s\in S, \tag{43}$$

$$w_n \geqslant e_n - t_{\max n}; \quad n\in N, \tag{44}$$

$$r_n \geqslant t_{\max n} - e_n; \quad n\in N, \tag{45}$$

$$\sum_{k\in K} v_k^1 u_{ns} \leqslant v_s^2; \quad n\in N; \quad s\in S, \tag{46}$$

$$\sum_{k\in K} m_k^1 u_{ns} \leqslant m_s^2; \quad n\in N; \quad s\in S, \tag{47}$$

$$\sum_{i\in I}\ \sum_{n\in N:(n,j)\in E}\ \sum_{s\in S:(f,s)\in P}\left(\sum_{l\in L} c^3_{sij}c^4_{sl}\frac{x_{nisl}}{t_{sij}}+\sum_{k\in K} c^5_{sk}p_{nk}u_{ns}\right)\geqslant b_{fj}v_{fj};$$

$$f\in F;\quad j\in J, \tag{48}$$

$$\rho_{ij},\ v_{fj},\ q_{fj},\ u_{ns},\ x_{nisl},\ y_{ni}\in\{0,1\};$$

$$f\in F;\quad i\in I;\quad j\in J;\quad l\in L;\quad n\in N;\quad s\in S, \tag{49}$$

$$e_n,\ r_n,\ w_n\geqslant 0,\ \text{ integer};\quad n\in N. \tag{50}$$

The minimized sum (30) represents the cost criterion which takes into account the following costs: purchase of products by individual recipients, with discounts granted by the selected suppliers; transport services, dependent on the selected transportation modes, transport duration, the number of the transported products (costs of loading, unloading), taking into account the discounts offered by the transportation companies; costs of storing the products supplied before the planned deadlines and penalties for delays in delivery of the products. The minimization of the sum (30) is used to find such schedules of deliveries in which the products are delivered in the periods as close to the given deadlines for task execution as possible.

The first group of constraints applies to the selection of suppliers. The dependencies guarantee: (31) – selection of the supplier for each order; (32) – reduction of the number of the selected suppliers by individual recipients; (33) – taking into consideration the availability of the suppliers of the ordered products in individual periods of time; (34) – making decision by individual suppliers about granting discount for the given recipients due to ordering the products whose price gives right to discount. Another group of mathematical dependencies has been built for organisation of transport of the products. The restrictions ensure: (35) – assigning the transportation modes for each order; (36) – building the list of the selected transportation companies by particular recipients; (37) – reducing the number of the selected transportation companies by particular recipients; (38) – including travel time for individual routes; (39) – execution within the given period of time of one order by a specific transportation mode at the most; (40) – continuity of transport tasks by particular transportation modes; (41) – determining the minimum breaks between transporting products to save time for travels to the suppliers (the break time is assumed to be equal to the time of the previous transport service); (42) and (43) – determining the time for delivery of the products for particular orders; (44) – determining delay in delivery of the products for particular orders; (45) – determining the time for early execution of the order; (46) – space for products in particular transportation modes; (47) – verification of the allowed weight of the products transported for the specific transportation modes; (48) – making the decision by transportation companies about granting discount for the recipient due to execution of the services whose cost gives right to discount. The conditions (49) and (50) include the appropriate types of variables.

4. Computational experiments

The conducted computational experiments were aimed at comparing the hierarchical approach H and the monolithic approach M. To support construction of mathematical models, the AMPL mathematical programming language is used (AMPL – *A Modelling Language for Mathematical Programming*) (Fourer *et al.*, 2003). The GUROBI solver (www.gurobi.com) was used for computational experiments. MPS format files were prepared for test instances. The computational experiments were provided for five groups of test instances for short-term planning (up to 7 days). 25 test instances were solved in each of the groups (for producers of machines). The parameters of these groups of test instances and the average values of the results are given in Table 7. Three indexes were used to compare the solution approaches H and M, defined as follows:

- λ – used for comparing the length of the schedules produced with the hierarchical approach H and with the monolithic approach M, determined according to (51), where: $C_{\max}^{\mathrm{H}}, C_{\max}^{\mathrm{M}}$ – the lengths of the schedules of transport tasks determined with the use of the M, H approaches;

$$\lambda = C_{\max}^{\mathrm{M}} / C_{\max}^{\mathrm{H}}, \tag{51}$$

- θ – used to compare the sums of costs related to support of the supply networks, calculated on the basis of (52), where: κ^{H}, κ^{M} – the costs determined with the use of the M, H approaches.

$$\theta = \kappa^{\mathrm{M}} / \kappa^{\mathrm{H}}, \tag{52}$$

- σ – used to compare the computational times, determined according to (53), where: CPU^{M1}, CPU^{M2} – the computational times connected with the use of the H, P approaches.

$$\sigma = CPU^{M} / CPU^{\mathrm{H}}. \tag{53}$$

The average values of the λ coefficient given in Table 7 showed that the shortest schedules of product deliveries were built with the use of the monolithic approach M, as they constituted 88–94% of the length of the schedules built with the hierarchical approach H. Another advantage of the monolithic approach M

Table 7: Parameters of groups of test instances and average values of results

Parameters of groups of test instances												Indexes		
Group	I'	J'	K'	F'	S'	ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	λ	θ	σ
1	3	3	12	3	8	1000	2000	3000	–	–	–	0.88	0.91	14.2
2	3	3	14	4	10	2000	4000	5000	–	–	–	0.89	0.93	16.1
3	3	4	16	5	12	4000	5000	5000	5000	–	–	0.92	0.93	17.3
4	4	4	18	6	14	5000	6000	7000	8000	–	–	0.94	0.95	20.5
5	6	6	20	6	18	5000	5000	6000	6000	8000	8000	0.94	0.94	24.4

Numbers of: I' – suppliers, J' – recipients, K' – types of products, F' – transportation companies, S' – transportation modes, ω_j – units of the all products transported to the recipient j.

comes in the form of lower costs of operation of the supply network – the values of the θ index show several per cent in cost reduction. It comes from shorter schedules and lower costs related to delayed deliveries. The benefits resulting from using the monolithic approach M are paid with longer time needed for the calculations. The calculations in the monolithic approach M take many times longer than in case of the multi-level approach H and increase considerably with the size of the problem being solved. The time of calculations for the test problems of the largest size and application of the hierarchical solution approach did not exceed 50 minutes.

Attention should be paid to the fact that the scale of the test instances was not significant, as they took into consideration the possibility of solving problems with the one-level solution approach (M). Another benefit from the monolithic approach M is thus the possibility of solving problems of significant size.

5. Conclusions

The presented methods proved to be effective in case of the diminishing market of fruits and vegetables, among which many products are seasonal. It is important when new suppliers are sought, presenting favourable offers.

The advantage of the prepared and compared approaches comes not only in the possibility of selection of suppliers and transportation companies, but also building schedules for execution of transport tasks with the selected transportation modes. Conducting an initial, multi-criteria selection of suppliers and transportation companies is important, thus limiting the number of input parameters and of the variables defined then for the problems to be solved.

The conducted computational experiments showed the possibility of simulations for checking the effect of input parameters on the length of the delivery schedule and the resulting costs. The problem of selection of the suppliers and transportation companies was solved with the presented solution approaches from the point of view of the interests of the whole network. The interests of individual links, including recipients, may be different, though.

The computational experiments were sued to measure defects and advantages of the presented solution approaches. They proved that the monolithic approach is recommended for solving problems of relatively small size. For larger-scale problems, the approach based on the hierarchic approach is proposed.

For both approaches, the models have been prepared for the integer programming problems. For each problem, the solution is found which is optimum from the point of view of the criteria assumed. Despite development in computer technology and software, some limitations persist as regards the size of the problem at hand. The resulting models may be the basis for building single-level or multi-level relaxation heuristics, in which problems of significant size may be solved at the cost of deviation from the optimum values. Their advantage comes in relatively short time used for calculations. The example of the work in which the mathematical model has been used for construction of relaxation heuristics is the article prepared by Magiera (2008).

The mathematical models built for the approaches may be modified and expanded. Development of models may be connected with storage of products, just as in the simultaneous optimization of storage and transport described by Sakakibara *et al.* (2012). Changes may also be applied to the regulations in granting discounts for the recipients by the suppliers or by the transportation companies. In the situation when the recipients create a network with one owner, the discounts may be granted to the whole network.

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