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WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2020.134410

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVI ISSUE 3 2020

THE OPTMIZATION TOOL SUPPORTING SUPPLY CHAIN MANAGEMENT IN THE MULTI-CRITERIA APPROACH

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The article presents a new optimization tool supporting supply chain management in the multi-criteria aspect. This tool was implemented in the EPLOS system (European Logistics Services Portal system). The EPLOS system is an integrated IT system supporting the process of creating a supply and distribution network in supply chains. This system consists of many modules e.g. optimization module which are responsible for data processing, generating results. The main objective of the research was to develop a system to determine the parameters of the supply chain, which affect its efficiency in the process of managing the goods flow between individual links in the chain. These parameters were taken into account in the mathematical model as decision variables in order to determine them in the optimization process. The assessment of supply chain management effectiveness was carried out on the basis of the global function of the criterion consisting of partial functions of the criteria described in the mathematical model. The starting point for the study was the assumption that the effectiveness of chain management is determined by two important decision-making problems that are important for managers in the supply chain management process, i.e. the problem of assigning vehicles to tasks and the problem of locating logistics facilities in the supply chain. In order to solve the problem, an innovative approach to the genetic algorithm was proposed, which was adapted to the developed mathematical model. The correctness of the genetic algorithm has been confirmed in the process of its verification.

Keywords: multi-criteria optimization, genetic algorithm, transport infrastructure, supply chain management

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1. INTRODUCTION

Supply chain management is a broadly discussed issue in the literature [1-13] and defined as goods and information flow management in supply chains. Management efficiency can be improved in different areas of the supply chain, e.g. transport, warehousing. This paper relates to the optimization of the efficiency of transport process management in supply chains. The operating supply chains differ among others in the type of entities participating in the process of supplying material demand to the production process or in the process of distributing finished products to the end customer, in the industry for which the supply chain is being built or in the specificity of the market. In order to clarify the considerations on the subject of supply chain efficiency, it was assumed that the supply chain analyzed in the paper consists of suppliers, intermediate points, e.g. storage facilities, and end customers, e.g. manufacturing companies. Throughout the supply chain, only road transport is considered.

Supply chain efficiency comes down primarily to the proper use of the existing equipment of the various elements of the chain to effectively achieve specific objectives. An important aspect of efficient supply chain management is to adapt its technical and human potential to the tasks. In the article, the supply chain efficiency was made dependent on two important decision-making problems encountered in the supply chain management process, i.e. the problem of locating facilities and the problem of allocating technical resources to specific tasks in the supply chain.

In the problem of the location of objects in the supply chain the logistics network is configured, i.e. suppliers, warehouse facilities are selected from among potential suppliers and warehouse facilities existing on the logistics services market [14-19]. The selection of suppliers and warehouse facilities depends on the costs of transport, purchase of a given raw material, storage costs. The distance determined between individual links and the amount of cargo transported in the chain determines the selection of the appropriate type of vehicle to carry out the transport task.

In the problem of assignment of vehicles to tasks, in transport problems [20-23] the appropriate vehicle type is assigned to the task, the number of vehicles of a given type is optimized and the route is determined.

The mathematical model presented in this article includes parameters that are important from the point of view of effective supply chain management. These parameters play the role of decision variables on the basis of which the optimal location of supply chain links is determined and the optimal allocation of vehicles to tasks is determined. These parameters refer to both processes carried out between links in the supply chain (transport) and processes taking place within a given link (reloading processes).

All the presented parameters influence the cost and time of cargo transport in the whole supply chain and thus play an important role in effective management of cargo flow in these chains.

Taking into account the multi-criteria approach, e.g. minimizing the cost of tasks, vehicles of the analyzed issue, various nature of decision variables used in the mathematical model, it is advisable to develop an innovative optimization algorithm adequate to the proposed mathematical model. Available optimization algorithms dedicated to multi-criteria issues [24] have a number of limitations in their use, e.g. compliance of the types of decision variables and cannot be used to solve this problem of effective supply chain management.

The genetic algorithm developed in this paper determines the main parameters of the supply chain affecting its effective operation. The algorithm has been adapted to the limitations and functions of the criteria described in the mathematical model.

The aim of this paper was to develop a new optimization tool supporting supply chain management in a multi-criteria aspect, which determines the suboptimal allocation of vehicles to tasks and the location of individual links in the supply chain, which, as stated in the above considerations, increases the efficiency of a given supply chain.

Take into account the above considerations in order to solve the parameters of the supply chain affecting its effective operation, the EPLOS was developed. The EPLOS system is an integrated IT system supporting the process of creating a supply and distribution network in supply chains. The system contains the modules which were presented on Fig. 1.

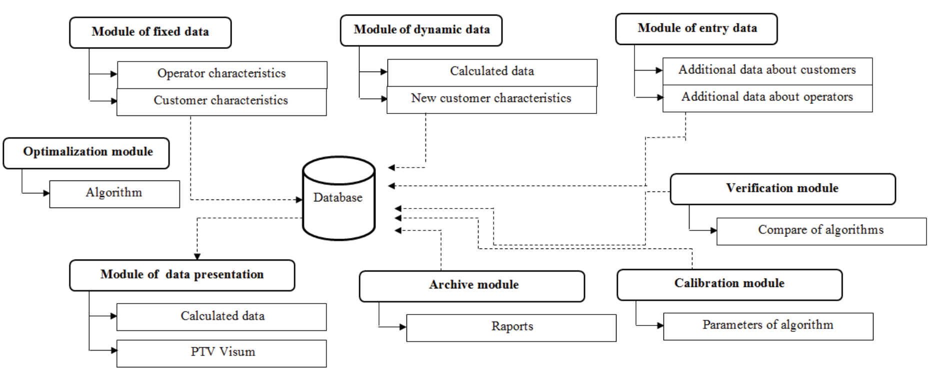

Fig. 1. The structure of the EPLOS system

Source: own work.

The EPLOS system was prepared in C# language, the graphic presentation of the results is presented in PTV VISUM 18 software. The module of fixed data contains the information about suppliers, recipients, the dynamic data module was designed to handle data that can be added, modified and deleted by users during system operation, e.g. loading, unloading points in the supply chain, the module of entry data was intended for handling the process of direct data input by the user, the data presentation module presents the results generating by system and cooperates with PTV VISUM software, the optimization module works based on the genetic algorithm, the archive module stores analysis reports and results, the calibration module sets and saves the parameters of the optimization algorithm, the verification module checks the correctness of results generated by the optimization algorithm. The modules such as fixed data module, the dynamic data module and he module of entry are based on the mathematical model of the analyzed supply chain.

2. SUPPLY CHAIN EFFICIENCY – LITERATURE REVIEW

Many studies show that efficient supply chain management is a key factor for success and competitive advantage [25-27]. Point elements of supply chains, i.e. warehouses and transshipment terminals, play an important role in effective functioning of supply chains. In these elements, cargo streams are transformed, delivery to final customers is delayed and thus losses and costs are generated [28,29]. Wong W.P. and Wong K.Y. [30] used the DEA (Data Envelopment Analysis) method to measure supply chain performance, proposing to use two separate deterministic DEA models: a technical efficiency model and a supply chain cost efficiency model. In their view, it is reasonable to use both models to analyze the chain scenario. Wu D. et al. [31] described a multi-stage MaxMin model to measure the performance and efficiency of supply chain participants and the entire system. Yu M. et al. [32] used stochastic models to study the impact of group and zone picking on the performance of the picking system.

Spitter et al. [33] proposed a model for constrained supply chain operations planning (SCOP). This model was used to evaluate the efficiency of production processes in the assumed supply chain structure at constant supply times. The model was based on scheduling mechanisms and could be used to increase the reliability of the supply chain due to production processes and inventory levels. Another approach to supply chain efficiency was presented by Sohn and Choi [34] who used fuzzy modeling to model the relationship between customer requirements and the required reliability of supply chain management solutions.

Rodrigues et al. [35] noted that most current research on supply chain efficiency focuses on the relationship between manufacturers and suppliers and that most of the models developed are based on this dual relationship. The authors added a third element – transport – as a natural complement to the model to study the supply chain in conditions of uncertainty. The resulting model better reflects the working conditions of the supply chain and indicates potential uncertainty reduction points. The model includes an uncertainty analysis from the point of view of the supplier, customer and carrier.

Rizzi and Zamboni [36] analyzed the quality of logistics processes using an ERP class IT system aimed at improving the internal logistic efficiency of the warehouse. The authors pointed out that the implementation of an integrated warehouse management information system alone does not guarantee the optimization of warehouse logistics. They pointed out that in order to improve the overall efficiency of logistics systems, the implementation of the ERP system should be combined with the redesign and reorganization of warehouse processes.

Supply chain management and the design of reliable distribution networks operating under normal and unforeseen disturbances can be found in the paper of Peng et. al. [37]. These authors proposed a mixed total number model to minimize the costs of logistic tasks while minimizing the risk of interruption of these tasks. Santoso et al. [38] presented a practical stochastic model for shaping supply chain development scenarios in conditions of uncertainty.

Olhager [39] addressed the issue of a just-in-time supply chain strategy and considered the role of this strategy in a variety of companies and its impact on supply chain efficiency.

Stephens [40], Li et al. [41] presented the use of the Supply Chain Operations Reference (SCOR) model to assess the quality, efficiency and performance of various aspects of the supply chain. This model was built on the basis of technical measures that allowed to describe different business processes in supply chains, thus it could be used in planning and evaluation of supply chains. The SCOR model was used for the description and comprehensive analysis of the supply chain. It allowed to measure, control and manage processes throughout the supply chain, involving all participants (producers, transport companies, distributors, consumers).

After analyzing the literature, it can be stated that the supply chains efficiency depends on the efficiency of individual processes taking place in these chains, e.g. transport and warehousing processes. Methods for determining efficient supply chains are mainly focused on simulation and probabilistic methods analyzing aspects of safety, reliability or risk. These methods do not optimize the parameters determining the chain efficiency, but only forecast the potential values that they can adopt. Taking into account the above analysis it can be stated that the mathematical model and genetic algorithm presented in the paper bring a new approach to efficient supply chain management and form the basis for further research on the implementation of genetic algorithms in the field of efficient supply chain management.

3. MATHEMATICAL MODEL OF THE SUPPLY CHAIN

The mathematical model was developed for the multi-criteria problem of supply chain management. The supply chain consists of suppliers of raw materials, storage facilities and a manufacturing company. The way of delivering raw material to the production company is possible in two relationships: direct i.e. supplier - company or indirect i.e. supplier - warehouse facilities - company. The choice of relationships depends on the technical and economic factors presented in the mathematical model. In the analyzed model it is assumed that the size of the transport tasks is not defined. Only the production company's demand for a given raw material is known. This means that the locations of raw material collection points and storage facilities are not known. Raw material collection points and storage facilities are selected from among potential suppliers offering raw material and storage facilities.

The transport task was defined as taking raw material from the loading point and transporting it to the unloading point. Tasks are assigned when the size of the cargo being moved between the links in the supply chain, the type of vehicles in the relation assigned to the tasks and their number are known. Depending on the size of the load to be transported and the capacity of the vehicle carrying out the transport, the number of transport tasks between the links in the chain may vary. The location of individual suppliers and storage facilities will be determined on the basis of designated tasks, which will determine the points of collection and unloading of raw materials.

The mathematical formulation of the decision model for the cargo flow model can be presented in the following way, for data**:** set of types of cargo ***H1***, size of cargo delivered by individual suppliers **QD1**, size of demand of cargo customers **QP1**, storage capacity of intermediate points **PMS1**, storage capacity of customers **PP1**, unit cost of cargo passage through storage facilities **JKP1**, time of task implementation **TP1**, set of links in supply chain ***LZ***, set of point elements in supply chain ***VZ***, matrix of distance between supply network objects **D1**, permissible time of implementation of transport tasks by means of external transport **TDOP1**, speed of a given type of external transport **V1**, set of types of external transport ***STZ1***, set of types of internal transport ***STW1***, set of drivers in external transport ***KLZ1***, set of drivers in internal transport ***KLW1***, loading time ***TZ1***, unloading time **TW1**, capacity of external means of transport **POJ1**, efficiency of practical means of internal transport **WP1**, number of internal means of transport **NW1**, number of external **NZ1** means of transport, operating costs of internal means of transport **KEW1**, unit cost of drivers' work in internal transport **JKW1**, permissible time of task completion in hierarchical networks **TDOP1**, unit cost of fuel consumption for a given type of external means of transport **KZP1** , the values of decision variables should be determined: value of *h1-type* stream transmitted between links in the supply chain Eq.(3.1), use of the given type of external transport for the transport tasks Eq. (3.2), number of the given type of external transport used for the connection Eq. (3.3), use of the given type of internal transport for the handling reloading tasks Eq. (3.4), number of the given type of internal transport Eq. (3.5), time of involvement of the given type of internal transport Eq. (3.6), time of involvement of the given type of external transport Eq. (3.7)

(3.1) $$\mathbf{X}1=\left[x1((w,w'),h1): x1((w,w'),h1)\in\mathcal{N},(w,w')\in\boldsymbol{LZ},h1\in\boldsymbol{H}1\right]$$

(3.2) $$\mathbf{Y}1=\left[y1((w,w'),st1): y1((w,w'),st1)\in\{0,1\},(w,w')\in\boldsymbol{LZ},st1\in\boldsymbol{STZ}1\right]$$

(3.3) $$\mathbf{N}1=\left[n1((w,w'),st1): n1((w,w'),st1)\in\mathcal{N},(w,w')\in\boldsymbol{LZ},st1\in\boldsymbol{STZ}1\right]$$

(3.4) $$\mathbf{Z}1=\left[z1(w,st1): z1(w,st1)\in\{0,1\},w\in\boldsymbol{VZ},st1\in\boldsymbol{STW}1\right]$$

(3.5) $$\mathbf{K}1=\left[k1(w,st1): k1(w,st1)\in\mathcal{N},w\in\boldsymbol{VZ},st1\in\boldsymbol{STW}1\right]$$

(3.6) $$\mathbf{TZS}1=\left[tzs1(w,st1): tzs1(w,st1)\in\mathcal{N},w\in\boldsymbol{VZ},st1\in\boldsymbol{STW}1\right]$$

(3.7) $$\mathbf{TZSH}1=\left[tzsh1((w,w'),st1): tzsh1((w,w'),st1)\in\mathcal{N},(w,w')\in\boldsymbol{LZ},st1\in\boldsymbol{STZ}1\right]$$

that meet the restrictions: restriction in the efficiency of the internal transport modes used Eq. (3.8), Eq. (3.9), restriction in the number of available internal transport modes Eq. (3.10), restriction in the time of the vehicle involvement resulting from time restrictions of the internal transport worker Eq. (3.11), restriction in the time of the vehicle involvement resulting from time restrictions of the external transport worker Eq. (3.12), restriction in the number of available external transport modes Eq. (3.13), Eq. (3.14), restriction of the permissible driving time of external transport vehicles Eq. (3.15), restriction of the driving time of vehicles resulting from the permissible driving time of drivers Eq. (3.16), restriction of task implementation time Eq. (3.17), production capacity of suppliers Eq. (3.18), production capacity of customers Eq. (3.19), capacity restrictions of intermediate points (warehouse facilities) Eq. (3.20), storage capacity of customers Eq. (3.21), restrictions concerning the preservation of the cargo stream flowing in and out of a given warehouse facility Eq. (3.22):

(3.8)
$$w \in \boldsymbol{D},\ st1 \in \boldsymbol{STW}1$$
$$\sum_{h1 \in \boldsymbol{H}1} wp1(st1, w, h1) \cdot tzs1(w, st1) \cdot k1(w, st1) \cdot z1(w, st1) \geq \sum_{(w,w') \in \boldsymbol{LDMS}} x1((w,w'), h1) + \sum_{(w,w') \in \boldsymbol{LDP}} x1((w,w'), h1)$$

(3.9)
$$w \in \boldsymbol{MS},\ st1 \in \boldsymbol{STW}1$$
$$\sum_{h1 \in \boldsymbol{H}1} wp1(st1, w, h1) \cdot tzs1(w, st1) \cdot k1(w, st1) \cdot z1(w, st1) \geq \sum_{(w,w') \in \boldsymbol{LMSP}} x1((w,w'), h1)$$

(3.10)
$$\forall w \in \boldsymbol{VZ},\ \forall st1 \in \boldsymbol{STW}1 \qquad k1(w, st1) \cdot z1(w, st1) \leq nw1(w, st1)$$

(3.11)
$$\forall w \in \boldsymbol{VZ},\ \forall st1 \in \boldsymbol{STW}1 \qquad tzs1(w, st1) \leq tdw1$$

(3.12)
$$\forall (w, w') \in \boldsymbol{LZ} \qquad tzsh1((w,w'), st1) \leq tdzr1$$

(3.13)
$$\forall w \in \boldsymbol{D},\ \forall st1 \in \boldsymbol{STZ}1 \quad \sum_{(w,w') \in \boldsymbol{LDP}} n1((w,w'), st1) \cdot y1((w,w'), st1) \leq nz1(w, st1)$$

(3.14)
$$\forall w \in \boldsymbol{MS},\ \forall st1 \in \boldsymbol{STZ}1 \quad \sum_{(w,w') \in \boldsymbol{LMSP}} n1((w,w'), st1) \cdot y1((w,w'), st1) \leq nz1(w, st1)$$

(3.15)
$$st1 \in \boldsymbol{STZ}1,\ (w, w') \in \boldsymbol{LZ}$$
$$2 \cdot \left\lceil \frac{\sum_{h1 \in \boldsymbol{H}1} x1((w,w'), h1)}{poj1(st1)} \right\rceil \cdot y1((w,w'), st1) \cdot \frac{d1(w,w')}{v1((w,w'), st1)} \leq tzsh1((w,w'), st1) \cdot n1((w,w'), st1)$$

(3.16)
$$st1 \in \boldsymbol{STZ}1,\ (w, w') \in \boldsymbol{LZ}$$
$$2 \cdot \left\lceil \frac{\sum_{h1 \in \boldsymbol{H}1} x1((w,w'), h1)}{poj1(st1)} \right\rceil \cdot y1((w,w'), st1) \cdot \frac{d1(w,w')}{v1((w,w'), st1)} \leq tdzr1 \cdot n1((w,w'), st1)$$

(3.17)
$$st1 \in \boldsymbol{STZ}1,\ (w, w') \in \boldsymbol{LZ}$$
$$2 \cdot \left\lceil \frac{\left\lceil \frac{\sum_{h1 \in \boldsymbol{H}1} x1((w,w'), h1)}{poj1(st1)} \right\rceil}{n1((w,w'), st1)} \right\rceil \cdot y1((w,w'), st1) \cdot \frac{d1(w,w')}{v1((w,w'), st1)} + \sum_{h1 \in \boldsymbol{H}1} x1((w,w'), h1) \cdot$$
$$\cdot [tz1(w, st1) + tw1(w', st1)] \leq tdop1(w, w')$$

(3.18)
$$\forall h1 \in \boldsymbol{H}1,\ \forall w \in \boldsymbol{D} \quad \sum_{w' \in \boldsymbol{MS}} x1((w,w'), h1) + \sum_{w' \in \boldsymbol{P}1} x1((w,w'), h1) \leq qd1(w, h1)$$

(3.19) $\forall h1 \in \boldsymbol{H}1,\ \forall w' \in \boldsymbol{P}1 \quad \sum_{w \in \boldsymbol{MS}} x1((w,w'),h1) + \sum_{w \in \in \boldsymbol{D}} x1((w,w'),h1) = qp1(w',h1)$

(3.20) $\forall w' \in \boldsymbol{MS} \quad \sum_{w \in \boldsymbol{D}} \sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1) \leq pms1(w')$

(3.21) $\forall w' \in \boldsymbol{P}1 \quad \sum_{w \in \boldsymbol{D}} \sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1) + \sum_{w \in \boldsymbol{MS}} \sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1) \leq pp1(w')$

(3.22) $\forall w' \in \boldsymbol{MS} \quad \sum_{w \in \boldsymbol{D}} \sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1) = \sum_{w \in \boldsymbol{P}} \sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1)$

so that functions with interpretation of the coefficient of the use of internal transport means Eq. (3.23), the coefficient of the use of external transport means Eq. (3.24), the minimum labor costs of internal transport means and internal transport staff Eq. (3.25), the total cost of carrying out transport tasks Eq. (3.26), the coefficient of the use of vehicles' involvement time Eq. (3.27), the total time spent on carrying out the load Eq. (3.28), the minimization of the number of vehicles Eq. (3.29) reach the minimum values:

$$\mathbf{WST}1 = \sum_{w \in \boldsymbol{D}} \sum_{st1 \in \boldsymbol{STW}1} \frac{k1(w,st1) \cdot z1(w,st1)}{nw1(w,st1)} + \sum_{w \in \boldsymbol{MS}} \sum_{st1 \in \boldsymbol{STW}1} \frac{k1(w,st1) \cdot z1(w,st1)}{nw1(w,st1)} + \sum_{w \in \boldsymbol{P}} \sum_{st1 \in \boldsymbol{STW}1} \frac{k1(w,st1) \cdot z1(w,st1)}{nw1(w,st1)} \longrightarrow \min \tag{3.23}$$

$$\mathbf{WZ}1 = \sum_{w \in \boldsymbol{D}} \sum_{st1 \in \boldsymbol{STZ}1} \mathbf{WSDMS}1(w,st1) + \sum_{w \in \boldsymbol{D}} \sum_{st1 \in \boldsymbol{STZ}1} \mathbf{WSDP}1(w,st1) + \sum_{w \in \boldsymbol{MS}} \sum_{st1 \in \boldsymbol{STZ}1} \mathbf{WSMSP}1(w,st1) \longrightarrow \min \tag{3.24}$$

$$\mathbf{FKW}1(\mathbf{KEW}1, \mathbf{TZS}1, \mathbf{K}1, \mathbf{Z}1) = \sum_{kl1 \in \boldsymbol{KLW}1} \sum_{w \in \boldsymbol{VZ}} \sum_{st1 \in \boldsymbol{STW}1} [kew1(w,st1) + jkw1(w,kl1)] \cdot tzs1(w,st1) \cdot k1(w,st1) \cdot z1(w,st1) \longrightarrow \min \tag{3.25}$$

$$\mathbf{FKB}1(\mathbf{X}1, \mathbf{Y}1, \mathbf{N}1) = \sum_{st1 \in \boldsymbol{STZ}1} \sum_{(w,w') \in \boldsymbol{LZ}} \left(2 \cdot \left\lceil \frac{\left\lceil \frac{\sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1)}{poj1(st1)} \right\rceil}{n1((w,w'),st1)} \right\rceil \cdot y1((w,w'),st1) \cdot d1(w,w') \cdot kzp1(st1) + \sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1) \cdot jkp1(w',h1) \right) \longrightarrow min \tag{3.26}$$

$$\mathbf{WJH}1 = \sum_{st1 \in \boldsymbol{STZ}1} \sum_{(w,w') \in \boldsymbol{LZ}} \mathbf{WJH}1(st1,(w,w')) \longrightarrow \min \tag{3.27}$$

$$\mathbf{FP}1(\mathbf{X}1, \mathbf{Y}1, \mathbf{N}1) = \sum_{st1 \in \boldsymbol{STZ}1} \sum_{(w,w') \in \boldsymbol{LZ}} \left(2 \cdot \left[\frac{\left[\dfrac{\sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1)}{poj1(st1)} \right]}{n1((w,w'),st1)} \right] \cdot y1((w,w'),st1) \cdot \frac{d1(w,w')}{v1((w,w'),st1)} + \sum_{h1 \in \boldsymbol{H}1} x1((w,w'),h1) \cdot \cdot [tz1(w,st1) + tw1(w',st1)] \right) \longrightarrow min \tag{3.28}$$

$$\mathbf{FN}1(\mathbf{N}1) = \sum_{st1 \in \boldsymbol{STZ}1} \sum_{(w,w') \in \boldsymbol{LZ}} n1((w,w'),st1) \cdot y1((w,w'),st1) \longrightarrow min \tag{3.29}$$

4. MATHEMATICAL MODEL OF THE SUPPLY CHAIN

4.1. GENEARL ASSUMPTION

In order to determine the parameters of the supply chain influencing its efficient operation (see the decision variables in the chapter 3), an innovative optimization algorithm based on the genetic algorithm described in the literature [42,43] was developed. The matrix structure has the interpretation of decision variables defined in the mathematical model. The reproductive process algorithm generates a population according to the roulette method principle, using linear scaling to counteract premature algorithm convergence in the initial iterations [42,43]. The final effect of the genetic algorithm is the generated population determining the optimal parameters of the chain. The stages of the algorithm: Stage 1. Development of the chromosome structure, Stage 2. Development of the adaptation function, Stage 3 and 4. Determination of crossover and mutation of chromosomes. Stages 2-4 are repeated by a specified number of iterations, until the moment of obtaining the stop condition. The stop condition is the specified number of iterations. The evaluation of individuals is carried out on the basis of the adaptation function, which is developed on the basis of multi-criteria functions (the chapter 3). This exemplary adaptation function (only for two criteria functions) for the *k-th* matrix structure $\mathbf{M}(t, k)$ can be presented as follows ($\boldsymbol{K} = \{1, \ldots, k, \ldots, K\}$- set of structures in population, t - iteration):

(4.1)
$$F(k,t) = \frac{F1\min(t)}{F1(k,t)} + \frac{F2\min(t)}{F2(k,t)} + \ldots \longrightarrow \min$$

where:

$F1(k,t)$ – coefficient of the use of means of internal transport calculated for k-th structure in t-iteration, $F1\min(t)$ – minimum value of the structure from the whole population in a given iteration determining the coefficient of internal transport mode use, $F2(k,t)$ – coefficient of the use of modes of external transport calculated for k-th structure in t-iteration, $F2\min(t)$ – minimum value of the structure from the whole population in a given iteration determining the coefficient of use of the mode of external transport and so on.

4.2. DEVELOPMENT OF THE CHROMOSOME STRUCTURE

The chromosome structure has been defined as a matrix describing individual decision variables in the distinguished submatrices. An example of a chromosome structure showing cargo flows in the supply chain (Variable 1), the use of a given means of external transport (Variable 2), the number of external and internal transport vehicles (Variable 3), the time of involvement of the means of external transport (Variable 4), the use of a given means of internal transport (Variable 5), the number of means of internal transport of a specific type (Variable 6), the time of involvement of the internal transport mode (Variable 7) is shown in Fig. 2.

	variable 1 – X1						variable 2 – Y1					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	20	10	50	0	0	0	1	1	1	0
D2	0	0	30	20	10	0	0	0	1	1	1	0
MS1	0	0	0	0	0	50	0	0	0	0	0	1
MS2	0	0	0	0	0	30	0	0	0	0	0	1
MS3	0	0	0	0	0	60	0	0	0	0	0	1
P1	0	0	0	0	0	0	0	0	0	0	0	0

	variable 3 – N1						variable 4 – TZSH1					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	5	3	6	0	0	0	3	7	6	0
D2	0	0	0	1	0	0	0	0	0	1	0	0
MS1	0	0	0	0	0	2	0	0	0	0	0	0
MS2	0	0	0	0	0	3	0	0	0	0	0	0
MS3	0	0	0	0	0	1	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0

	variable 5 – Z1						variable 6 – K1					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	1	1	1	0	0	0	2	1	2	0
D2	0	0	0	1	0	0	0	0	2	3	1	0
MS1	0	0	0	0	0	1	0	0	0	0	0	2
MS2	0	0	0	0	0	0	0	0	0	0	0	1
MS3	0	0	0	0	0	1	0	0	0	0	0	1
P1	0	0	0	0	0	0	0	0	0	0	0	0

	variable 7 – TZS1						**Division of the stream 1 [%]**					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	4	3	5	0	0	0	0	0	0	0
D2	0	0	3	1	6	0	0	0	0	0	0	0
MS1	0	0	0	0	0	3	0	0	0	0	0	0
MS2	0	0	0	0	0	5	0	0	0	0	0	0
MS3	0	0	0	0	0	1	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0

	Division of the stream 2 [%]					
	D1	D1	D1	D1	D1	P1
D1	0	0	0	0	0	0
D2	0	0	0	0	0	0
MS1	0	0	0	0	0	0
MS2	0	0	0	0	0	0
MS3	0	0	0	0	0	0
P1	0	0	0	0	0	0

Fig. 2. Chromosme matrix structure

Source: own work.

The rows and columns of this matrix define the links in the supply chain in each part. In order to determine the cargo flow, the rows are defined as the starting points from which the cargo flows to the other links. The matrix cells are set in the following order: suppliers (D1-D2), warehouses (MS1-MS3) and customers - manufacturing company (P1). In the substructures Stream division 1 and stream division 2, the percentage shares of the cargo flow between the different types of external vehicles and the division of the cargo flow into the different modes of internal transport are placed at random.

4.3. CROSSOVER AND MUTATION PROCESS

The crossover process begins with the random selection of two chromosomes. In order to carry out the crossover process, it is necessary to specify the crossing parameter (the probability of crossover and mutation). The process of chromosome crossover is carried out in two ways, depending on the values taken by the decision variables. In the first instance, the chromosome selects randomly the substructure to be crossed over.

Where a randomly drawn substructure specifies decision variables from Variable 2 – Variable 7 then two cutting points are randomly selected and values of two chromosomes to be crossed over are exchanged between these cutting points. A graphic interpretation of the crossover of the two substructures defining the vehicle types is presented in Fig. 3.

	Variable 2 – Y1						Variable 2 – Y1					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	1	0	1	0	0	0	1	1	1	0
D2	0	0	1	1	1	0	0	0	1	1	0	0
MS1	0	0	0	0	0	1	0	0	0	0	0	1
MS2	0	0	0	0	0	1	0	0	0	0	0	0
MS3	0	0	0	0	0	1	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0

a

	Variable 2 – Y1						Variable 2 – Y1					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	1	0	1	0	0	0	1	1	1	0
D2	0	0	1	1	0	0	0	0	1	1	1	0
MS1	0	0	0	0	0	1	0	0	0	0	0	1
MS2	0	0	0	0	0	0	0	0	0	0	0	1
MS3	0	0	0	0	0	0	0	0	0	0	0	1
P1	0	0	0	0	0	0	0	0	0	0	0	0

b

Fig. 3. a) Substructures before crossover, b) Substructures after crossover

Source: own work.

For Variable 1, Variable 8 or Variable 9 two matrices have been developed to complete the crossover process: **DIV**, which contain the rounded average values of both parents and a **REM** matrix indicating whether the rounding was really necessary [43]. A graphic presentation of the crossover process is shown in Fig. 4. REM matrix values are added to the DIV matrix. Two new structures are created as a result of this operation.

	Variable 1 – X1						Variable 1 – X1					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	20	10	50	0	0	0	25	25	30	0
D2	0	0	30	20	10	0	0	0	20	20	20	0
MS1	0	0	0	0	0	50	0	0	0	0	0	45
MS2	0	0	0	0	0	30	0	0	0	0	0	45
MS3	0	0	0	0	0	60	0	0	0	0	0	50
P1	0	0	0	0	0	0	0	0	0	0	0	0

a

	DIV						REM					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	22	17	20	0	0	0	1	1	0	0
D2	0	0	25	20	15	0	0	0	0	0	0	0
MS1	0	0	0	0	0	47	0	0	0	0	0	1
MS2	0	0	0	0	0	37	0	0	0	0	0	1
MS3	0	0	0	0	0	55	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0

b

	DIV						REM					
	D1	D2	MS1	MS2	MS3	P1	D1	D2	MS1	MS2	MS3	P1
D1	0	0	23	17	20	0	0	0	22	18	20	0
D2	0	0	25	20	15	0	0	0	25	20	15	0
MS1	0	0	0	0	0	48	0	0	0	0	0	47
MS2	0	0	0	0	0	37	0	0	0	0	0	38
MS3	0	0	0	0	0	55	0	0	0	0	0	55
P1	0	0	0	0	0	0	0	0	0	0	0	0

c

Fig. 4. a) Substructures for crossover, b) DIV and REM matrices, c) New substructures after crossover

Source: own work.

Mutation of substructures with binary decision variables, i.e. Variable 2 , Variable 5 is a random conversion of gene values from 1 to 0 or from 0 to 1. Mutation of substructures with variable integer type I, i.e. Variable 3, Variable 4, Variable 6, Variable 7 consists in a random selection of a substructure cell and then a random change of its value. In the case of variables concerning the size of the cargo flow stream, i.e. Variable 1 and the division of this stream Stream division, the integer mutation type II consists in randomly generating the submatrix with dimensions $p \times q$ (k - number of lines in the substructure, e.g. part I, n - number of columns in this substructure), where p and q from the range of: $2 \leq p \leq k$ and $2 \leq q \leq n$, which define the number of lines and columns of the submatrix [43]. The generated matrix is modified in such a way that the total value in columns and rows before and after the modification process does not change.

5. CASE STUDY

5.1. THE CHARACTERISTICS OF THE STUDIED AREA

The model was verified using the example of a production company operating on the domestic market with respect to the production of hardware for roof windows. Cargo loading points are suppliers located in different parts of the country. The entire batch of raw material is transported once, i.e. all raw material must be collected from warehouses or suppliers in accordance with the applicable production schedule. Orders are placed in pallet load units. The data input was presented in the Table 1-4. Technical potential are VOLVO FH vehicles (available from suppliers), "standard" type semi-trailer - 34 pallets, vehicle combustion 33 l/100, and SCANIA R 520 V8 (available in warehouses), "standard" type semi-trailer - 34 pallets, vehicle combustion 30 l/100. In addition, it was assumed for the verification of the model that the average speed between the objects of the network is 60 km/h, the fuel cost is 6 PLN/l. The capacity of the production warehouse has been adjusted to 150 pallet units, while the cost of a pallet transition through the warehouse is PLN 25. A graphic interpretation of the supply chain links is shown in Fig. 5.

Table 1. Characteristics of warehouse facilities in the supply chain

Number M	Warehouses	Volume [palette load unit]	Cost of transition [PLN]	Number of vehicles SCANIA R 520 V8	Loading and unloading time
9-M1	Lubartów	300	11	12	5/6
10-M2	Minsk Mazowiecki	250	14	11	5/5
11-M3	Sokołów Podlaski	230	15	7	4/6

Source:own work.

Table 2. Supplier characteristics including internal transport

Number D	Suppliers	Production capacity (palette load unit)	Number of vehicles VOLVO FH	Loading times [min.]	Number of modes of internal transport	Efficiency of internal transport modes [palette load unit/h]	Costs of operating internal transport modes [PLN/h]	Unit cost of drivers' labor in internal transport [PLN/h]
1-D1	Warsaw	350	12	5	7	50	12	20
2-D2	Białystok	150	15	5	8	40	15	10
3-D3	Radom	350	10	4	6	55	10	20
4-D4	Ostrołęka	100	11	6	8	60	11	15
5-D5	Płock	250	8	6	7	70	13	18
6-D6	Łódź	130	9	5	5	60	10	15
7-D7	Chełm	140	12	4	10	80	12	14
8-D8	Kielce	220	7	5	11	50	15	12

Source: own work.

Table 3. Characteristics of available modes of internal transport in warehouse facilities

Number	Warehouses	Efficiency of internal transport modes [palette load unit]	Number of modes of internal transport	Costs of operating internal transport modes [PLN/h]	Unit cost of drivers' labor in internal transport [PLN/h]
9-M1	Lubartów	60	10	12	18
10-M2	Minsk Mazowiecki	50	11	10	15
11-M3	Sokołów Podlaski	55	6	11	10

Source: own work.

Table 4. Order of the manufacturing plant (customers)

Customer's number	Customer's name	Demand (palette load unit)				
		Monday	Tuesday	Wednesday	Thursday	Friday
12-P1	Radzyń Podlaski	160	-	140	-	300

Source: own work.

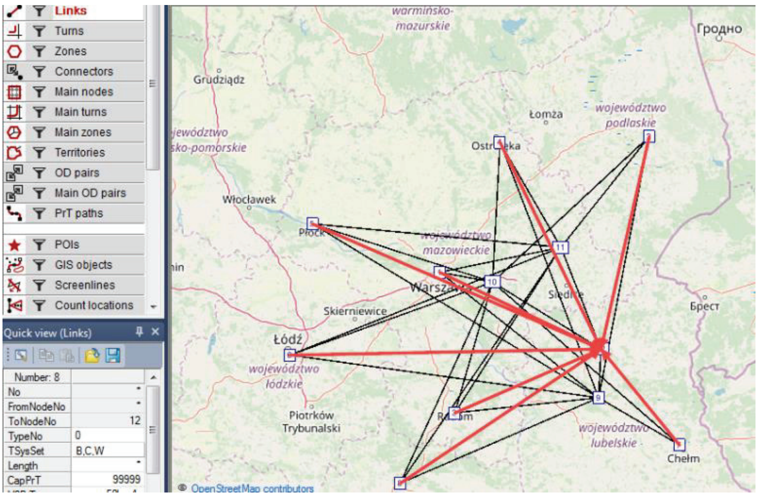

Fig. 5. Supply chain links

Source: own work based on PTV Visum

5.2. ALGORITHM SENSITIVE ANALYSIS

The first step in analyzing the sensitivity of an algorithm is to find the best set of parameters that characterize it. The parameters analyzed were the probability of crossover $p_{krzyż}$, probability of mutation p_{mut}. The following combinations have been tested to determine the best parameter settings, Table 5. The results are presented in Table 6, the best solution is generated in setting 9. the

Table 5. Test settings of the genetic algorithm

No.	$p_{crossover}$	p_{mut}	No.	$p_{crossover}$	p_{mut}	No.	$p_{crossover}$	p_{mut}
1	0.2	0.01	6	0.2	0.03	11	0.2	0.05
2	0.4	0.01	7	0.4	0.03	12	0.4	0.05
3	0.6	0.01	8	0.6	0.03	13	0.6	0.05
4	0.8	0.01	9	0.8	0.03	14	0.8	0.05
5	1	0.01	10	1	0.03	15	1	0.05

Source: own work.

Table 6. Sensitivity analysis of the genetic algorithm

Test	Value of the adaptation function	Test	Value of the adaptation function	Test	Value of the adaptation function
1	0.77	6	0.87	11	0.73
2	1.82	7	1.47	12	1.82
3	2.13	8	2.52	13	2.32
4	3.53	9	3.81	14	3.23
5	2.74	10	2.93	15	2.73

Source: own work.

In order to verify the validity of the genetic algorithm (AG), its results (test 9 for the best parameters) were compared with random values (AL). In each case, the genetic algorithm generated a better solution than the random algorithm, Table 7.

Table 7. Verification of the genetic algorithm

No.	AG	AL	No.	AG	AL	No.	AG
1	3.81	1.05	11	3.83	1.54	21	3.93
2	3.88	1.21	12	4.11	1.35	22	3.81
3	4.21	1.32	13	3.88	1.72	23	4.21
4	4.13	1.25	14	3.93	1.29	24	4.13
5	4.31	1.37	15	4.11	1.14	25	3.91
6	3.91	1.32	16	3.97	1.38	26	4.31
7	4.36	1.63	17	3.93	1.43	27	4.11
8	3.99	1.34	18	3.71	1.28	28	4.51
9	3.79	1.25	19	4.12	1.92	29	3.85
10	3.95	1.24	20	4.13	1.23	30	3.94

Source: own work.

6. SUMMARY

The aim of the article was to present an innovative system for determining the optimal parameters of the supply chain affecting its effectiveness in the performance of specific tasks. The developed EPLOS system works based on the genetic algorithm.

It should be noted that the presented genetic algorithm was used to solve a specific supply chain of a given mathematical model. The presented mathematical model is an original model which has not been analyzed before in the literature, therefore it is not possible to compare the results obtained by other methods with the results obtained by the developed genetic algorithm. Comparison of the results of the genetic algorithm proposed in the paper with another optimization algorithm is possible if a new optimization algorithm is developed, e.g. a ant algorithm widely described in the literature.

The development of new mathematical models taking into account additional parameters influencing the efficiency of supply chains, e.g. the introduction of risk functions in the performance of tasks, is a further step in testing the effectiveness of genetic algorithms in the field of efficient supply chain management. Further research may also involve testing other selection methods. It is also necessary to take into account the randomness of certain parameters such as travel time and reliability of transport modes.

It is worth noting that the presented algorithm is a starting point for testing other algorithms within the defined research problem. The comparison of random results with the results generated by the proposed genetic algorithm emphasizes the effectiveness of its action in the discussed problem. The results generated by means of genetic algorithms are the basis for further work on the development of new algorithms in the context of the examined problem.

Acknowledgment

Work performed within the framework of the EUREKA project implemented on the basis of an agreement with the National Center for Research and Development No. EUREKA / EPLOS / 3/2017. on the European Logistics Services Portal (EPLOS).

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LIST OF FIGURES AND TABLES:

OPTYMALIZACYJNE NARZĘDZIE WSPOMAGAJĄCE ZARZĄDZANIE ŁAŃCUCHEM DOSTAW W UJĘCIU WIELORYTERIANYM

Słowa kluczowe*: optymalizacja wielokryterialna, algorytm genetyczny, infrastruktura transportowa, zarządzanie łańcuchem dostaw*

STRESZCZENIE

W artykule przedstawiono nowe narzędzie optymalizacyjne wspierające zarządzanie łańcuchem dostaw w aspekcie wielokryterialnym. To narzędzie zostało wdrożone w systemie EPLOS (Europejski Portal Usług Logistycznych). System EPLOS to zintegrowany system informatyczny wspierający proces tworzenia sieci dostaw i dystrybucji w łańcuchach dostaw. Ten system składa się z wielu modułów, np. moduł optymalizacji odpowiedzialny za przetwarzanie danych, generowanie wyników, moduł danych wejściowych, moduł kalibracji parametrów algorytmu optymalizacyjnego. Głównym celem badań było opracowanie systemu do określania parametrów łańcucha dostaw, które wpływają na jego efektywność w procesie zarządzania przepływem towarów między poszczególnymi ogniwami łańcucha. Parametry te zostały uwzględnione w modelu matematycznym jako zmienne decyzyjne w celu ustalenia ich w procesie optymalizacji. W modelu matematycznym zdefiniowano dane wejściowe adekwatne do analizowanego problemu, przedstawiono główne ograniczenia związane z wyznaczaniem efektywnego sposobu zarządzania łańcuchem dostaw oraz opisano funkcje kryterium. Problem zarządzania przepływem towarów w łańcuchu dostaw został przedstawiony w ujęciu wielokryterialnym. Ocenę efektywności zarządzania łańcuchem dostaw przeprowadzono na podstawie globalnej funkcji kryterium składającej się z częściowych funkcji kryteriów opisanych w modelu matematycznym. Główne funkcje kryteriów na podstawie których wyznaczane jest końcowe rozwiązane to współczynnik wykorzystania wewnętrznych środków transportu, współczynnik wykorzystania zewnętrznych środków transportu, koszty pracy środków transportu wewnętrznego i personelu, całkowity koszt realizacji zadań transportowych, współczynnik wykorzystania czasu zaangażowania pojazdów, całkowity czas poświęcony na wykonanie zadań, czy liczba pojazdów.

Punktem wyjścia do badania było założenie, że o skuteczności zarządzania łańcuchem decydują dwa problemy decyzyjne ważne dla menedżerów w procesie zarządzania łańcuchem dostaw, tj. problem przydziału pojazdów do zadań i problem lokalizacji obiektów logistycznych w łańcuchu dostaw. Aby rozwiązać badany problem, zaproponowano innowacyjne podejście w postaci opracowania algorytmu genetycznego, który został dostosowane do przedstawionego modelu matematycznego. W pracy szczegółowo opisano poszczególne kroki konstruowania algorytmu. Zaproponowana struktura przetwarzana przez algorytm jest strukturą macierzową, dzięki której wyznaczane są optymalne parametry łańcucha dostaw. Procesy krzyżowania i mutacji zostały opracowane adekwatnie do przyjętej struktury macierzowej. W procesie kalibracji algorytmu wyznaczono takie wartości parametrów algorytmu tj. prawdopodobieństwo krzyżowania czy mutacji, które generują optymalne rozwiązanie. Poprawność algorytmu genetycznego oraz efektywność zaproponowanego narzędzia wspomagającego proces zarządzania łańcuchem dostaw została potwierdzona w procesie jego weryfikacji.

Received: 19.03.2020 Revised: 04.06.2020