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THE USE OF A SUPPLY CHAIN CONFIGURATION MODEL TO ASSESS THE RELIABILITY OF LOGISTICS PROCESSES

ZASTOSOWANIE MODELU KONFIGURACJI ŁAŃCUCHA DOSTAW DO OCENY NIEZAWODNOŚCI REALIZACJI PROCESÓW LOGISTYCZNYCH*

The article presents an approach to assessing the reliability of logistics processes implemented in supply chains in terms of time losses resulting from the selection of a variant of material flows in the supply chain. In order to define this indicator, a mathematical model of the supply chain has been developed, i.e. the parameters of the research problem, the decision variables, the constraints and the evaluation criteria. The method of evaluating the reliability of the system is presented in diagram form. The algorithm was verified based on experimental data. In order to evaluate the reliability of the logistic processes for the sample supply chain, a simulation model was developed that determines the time losses in the points and linear elements of the examined chain. Time losses are dictated by traffic delays resulting from traffic congestion on particular sections of the route and road junctions and delays in point elements in the supply chain.

Keywords: *reliability of logistic processes, loss of time in logistic processes, supply chain, simulation models.*

W artykule przedstawiono podejście do oceny niezawodności procesów logistycznych realizowanych w łańcuchach dostaw w aspekcie strat czasu wynikających z wyboru wariantu realizacji przepływów materiałowych w łańcuchu dostaw. Na potrzeby tych badań opracowano model matematyczny łańcucha dostaw, tj. określono parametry problemu badawczego, zmienne decyzyjne, ograniczenia oraz kryteria oceny. Sposób oceny niezawodności systemu został przedstawiony w postaci schematu. Algorytm został zweryfikowany na podstawie danych eksperymentalnych. W celu oceny niezawodności procesów logistycznych dla przykładowego łańcucha dostaw opracowano model symulacyjny wyznaczający straty czasu w elementach punktowych i liniowych badanego łańcucha. Straty czasu podyktowane są opóźnieniami w ruchu drogowym wynikającymi z kongestii ruchu na poszczególnych odcinkach trasy i węzłach drogowych oraz opóźnieniami w elementach punktowych łańcucha dostaw.

Słowa kluczowe: *niezawodność procesów logistycznych, straty czasu w procesach logistycznych, łańcuch dostaw, modele symulacyjne.*

1. Introduction

The supply chain is generally understood as a group of companies such as mining, production or distribution companies, etc., which carry out joint activities necessary to satisfy the demand of final recipients for specific products. The coordination of activities is carried out throughout the whole chain of goods flow from the acquisition of raw materials to deliveries to the final recipient. These activities may include: development, production, sale, maintenance, procurement, distribution, resource management, support activities, etc. The role and location of individual companies – entities in the structure of the supply chain – results from the division of labour at subsequent stages of production and sale of products. Intersecting supply chains constitute a network of relations of interdependent organisations which, acting on the basis of mutual cooperation, jointly manage the material goods flows and information from suppliers to final customers, control and improve them [1, 4, 17, 21, 22, 23, 24, 36, 21]. It may therefore be said that entities operating in the supply chain through links with suppliers and recipients are involved in various processes and activities that create value in the form of products and services delivered to final consumers. Each of the companies integrated in the supply chain is responsible for a part of the realized flows between entities.

There are many unpredictable situations in material goods flows which have a negative impact on the continuity and quality of these flows. The main operational risks[1] in this respect from the point of view of an established cell of the supply chain result from the following adverse events:

– delivery delay, e.g. due to: organisational disruptions at the supplier, lack of availability of ordered materials at the supplier, late delivery of the means of transport for loading, wrong selection of transport route, road conditions, delivery errors, extended customs clearance,

1 In general, risk assessments also distinguish legislative, financial and strategic risks [36].

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

– too fast delivery, e.g. due to delayed delivery of the means of transport for loading, road conditions,
– incomplete delivery, e.g. due to non-availability of all ordered materials from the supplier and damage or theft during transport,
– inadequate quality of the goods delivered, e.g. due to failure to meet the required transport conditions,
– damage to stored material goods,
– ageing (spoilage) of stored material goods,
– theft of stored material goods,
– breakdowns of internal transport equipment and other warehouse equipment,
– workers' strikes,
– accidents at work,
– atypical, very large customer orders,
– IT system failures,
– natural disasters and extraordinary events.

The listed adverse events have an unquestionable impact on the continuous flow of material goods, including the ability to meet customer demand, although this impact is minimised with varying degrees of success through the use of well-thought-out inventory management strategies. Nevertheless, the assessment of these strategies should also be carried out taking into consideration their impact on the reliability of logistics processes.

From the point of view of the reliability of supply processes in the logistics chain, the following indicators are distinguished: punctuality of deliveries, reliability of deliveries (complete delivery of ordered goods of appropriate quality), as well as readiness for delivery, and quality and flexibility of deliveries. The latter relate to the ability of suppliers to respond in emergency situations. Of course, the reliability of logistics processes in supply chains is always determined by the so-called weak links.

Researching the reliability of complex systems, such as the supply chain, requires a number of factors to be considered. The effectiveness of the supply chain is determined by the effectiveness of its operation. An important aspect is the dimensioning of factors that affect the effectiveness of supply chain operations, especially those aspects of supply chain operations that affect its reliability. One of the important determinants of the supply chain reliability is the timeliness of logistics processes. With this in mind, for an established structure of the supply chain, an approach to evaluating the reliability of the supply chain due to time losses resulting from various types of delays in the performance of tasks has been proposed.

2. State of knowledge

In technology, the dependability of a system (technical object) is usually defined as a set of properties that describe the readiness of the object as well as the reliability, maintainability and maintenance support that affect it. The term 'dependability' is used only for general quality description of technical object properties.

Nowakowski [30] draws attention to the following basic differences in the application of the reliability theory apparatus to describe technical objects and logistics processes:
– dependability is understood as a measure of task completion in time, which may be compared to the notion of reliability,
– the concept of readiness is used in a similar way in both logistical and technical terms,
– from the logistics point of view, there is no equivalent of the characteristics of maintainability or repairability (activities preventing the occurrence of errors are not assessed, as there are no indicators characterising the removal of the effects of the error),
– all measures are in the form of coefficients or structure indicators – no other characteristics are used, even though the assessed processes are random processes.

Thus, according to [30] the reliability of the supply chain means, among others: timely completion of the task, complete fulfilment of the order, receipt and release of goods without any damage.

To research the responsiveness and reliability of supply chain elements, i.e. to determine whether or not supply chain relations have a high reliability coefficient, companies use the Supply Chain Operation Reference Model (SCOR) [38]. The SCOR model is used to describe and analyse the supply chain in a comprehensive manner [18, 28, 39]. It allows processes throughout the supply chain to be measured, controlled and managed, covering all participants (manufacturers, transport companies, distributors and consumers).

The delivery reliability as indicated by Twaróg [41] is the quotient of timely deliveries to the total number of orders. The delivery quality may be measured by the quotient of the number of complaints and the total number of orders. On the other hand, the delivery flexibility (the ability to adapt to customer needs) may be determined by the quotient of the number of special requests fulfilled to the number of special requests. The delivery readiness may be expressed by the quotient of the number of orders delivered from the warehouse to the total number of orders. On the other hand, according to [27] and [29], the reliability is one of the non-quantifiable factors taken into consideration when designing logistics systems. A measure of operational reliability is a disturbance or the extent of decrease in efficiency. In this context, the flexibility of the system, i.e. adaptability, is analysed.

Numerous studies of the supply chain reliability problems consider the issues of system efficiency decrease and changes in the load capacity of displacement routes ([2, 3, 5, 7, 10]). By contrast, the studies on reliability of network of connections described in [8] and [11] focus mainly on connectivity and reliability during the journey.

One of the approaches to the supply chain reliability analysis is Fault Tree Analysis [16], which is a probabilistic approach allowing for the analysis of safety, reliability or risk. The Dynamic Fault Tree (DFT) method has been described, among others, in [12] and [13]. It was assumed that dynamic DFT gates can define:
– dynamic replacement of damaged components with spare components,
– occurrence of damage only in a predetermined order.

The use of a four-step model for the optimisation of the distribution network within the supply chain using the grey systems theory to take into account the uncertainties of phenomena and information was proposed in [44]. However, the issues of reducing the risk of supply chain disruption are described in [9]. It has been pointed out that the basic methods of risk reduction, i.e. creating reserves, increasing the efficiency of logistics facilities and cooperation with many suppliers, significantly increase costs. Therefore, increasing the supply chain efficiency means increasing the flexibility of the examined chain to adapt to adverse events and reduce risk. Increased supply chain flexibility without reducing its efficiency in relative terms may be achieved by segmenting the supply chain as well as configuring and adapting particular cells to the requirements of the surroundings. A similar approach is described in [26], using the concept of agility of the supply chain.

Another approach to supply chain reliability was proposed in [37], where fuzzy modelling was used to model the relations between customer requirements and the required reliability of solutions in the context of supply chain management.

It was noted in [34] that most current research on uncertainty and hence the supply chain efficiency and effectiveness focuses on the relations between manufacturers and suppliers, and most of the developed models are based on this dual relation. Thus, it adds a third element – a key logistics operation – transport, as a natural complement to the model for researching the supply chain under conditions of uncertainty. As a result, the obtained model reflects in a better way the working conditions of the supply chain and indicates potential points for reducing uncertainty. The model described in [34] includes the uncertainty analysis from the supplier, customer and carrier point of view.

According to the above, the issues of the supply of material goods often have to take into account elements of uncertainty, such as customer demand or driving time of vehicles. This is related to the dynamic vehicle routing (VRP) problem. When solving these problems, information that is the subject of uncertainty is updated through the use of the latest technologies, such as GPS or various types of telematics systems. The results of research carried out in this area may be found in, among others [6, 31, 32, 33]. The issues of searching for the shortest routes are still very topical. Many researchers dealing with this problem are looking for effective algorithms for finding the shortest routes (e.g. [19, 20, 25, 40, 46]).

Efficiency, productivity and the way logistics processes are carried out are strongly influenced by various types of random phenomena. Sources of random phenomena may be located both in warehouse facilities or management systems operating therein, as well as in close and distant surroundings. Due to the randomness of phenomena that determine the way processes are carried out in logistics facilities, an approach using the stochastic process theory apparatus is very often applied during the examination of these facilities [43].

The theory of mass handling and simulation studies are widely used in research and analysis of supply chains in terms of reliability of processes carried out therein ([2, 3, 14, 15, 42, 45]).

Bearing in mind undertaken in literature aspects of evaluating the supply chain reliability, the aim of the research was to develop a supply chain configuration model, which, taking into consideration the evaluation of the reliability of logistics processes in supply chains due to the total time losses resulting from traffic congestion on particular sections of the route and road junctions and delays in point elements of the supply chain, will enable the selection of the best variant of the supply chain configuration. At the same time, it is important to emphasise the possibility of using various variants of the supply chain configuration by including intermediate storage facilities in the physical flows. This reduces the need for small-tonnage vehicles and, consequently, the negative effects of transport.

Regardless of the variant of the supply chain configuration, both the handling times of physical streams at point elements of the supply chain and at transport connections between them are mapped by random variables (resulting from the traffic conditions existing at the moment). In this context, logistics processes in supply chains are stochastic processes.

With this in mind, it may be concluded that the performance times of physical flows in the supply chain are strictly dependent on random factors, e.g. failure of the internal transport device or vehicle, accidents, control errors, human errors, accumulation in flows. These, in turn, determine the reliability of a given logistics process. It is therefore important to develop a method for assessing the reliability of logistics processes in terms of the time needed to complete these processes, and in particular in terms of time losses. Time losses are understood here as an extension of the time of execution of a given process in relation to the nominal time of its execution. In the design practice, various coefficients are taken into consideration which represent the extension of the nominal time of a given activity (e.g. coefficients of working conditions), or functional dependencies (e.g. the function of the average speed of a given process depending on the number of units serviced), however, emergency events are ignored here. Moreover, in the literature there is no method of supply chain configuration taking into consideration the evaluation of the reliability of logistics processes due to the total time losses.

3. Supply chain configuration model due to reliability of execution of logistics processes

From the point of view of the reliability of the logistics process, all elements (cells) of the supply chain must meet specific efficiency expectations. This means that these cells may be regarded as a whole series reliability system. The unreliability of one or more cells translates into the unreliability of the entire chain. Conversely, the reliability of particular cells in the supply chain means that it can meet efficiency expectations in all areas of its surroundings. At the same time, it should be stressed that the optimisation of logistics solutions is always carried out simultaneously, taking into account the quality assessment criteria (service level) and the criteria for assessing the costs of logistics processes. This results in a multi-criteria approach or (in the classical sense) a single-criteria approach, where the assessment criterion is cost and the quality assessment indicators are recognised in constraints. With this in mind, and in view of the objective of the research, a supply chain configuration model has been proposed which takes into consideration two criteria for assessing solutions (costs and probability of occurrence of time losses) and, among the constraints, additional requirements for the implementation of logistics processes within a certain time frame have been taken into account. In this model, the following values were taken into account among the data characterising the above-mentioned functions of the criteria:

- a set of variants of the supply chain configuration: $\boldsymbol{LD} = \{ld: ld = 1, \ldots, LD\}$,
- sets of numbers of cells of the supply chain in variants of its configuration, $\boldsymbol{V}(ld)$, $ld \in \boldsymbol{LD}$,
- sets of relations between cells in variants of the supply chain configuration, $\boldsymbol{LF}(ld)$, $ld \in \boldsymbol{LD}$,
- sets of beginnings of relations of displacement of goods $\boldsymbol{A}(ld)$ and sets of ends of these relations in the variants of the supply chain $\boldsymbol{B}(ld)$, $ld \in \boldsymbol{LD}$,
- sets of numbers of routes which, in variants of the supply chain configuration may combine beginnings with ends of displacement relations, $\boldsymbol{E}(ld, a, b)$, $ld \in \boldsymbol{LD}$, $a \in \boldsymbol{A}(ld)$, $b \in \boldsymbol{B}(ld)$,
- sets of arcs forming routes in particular relations, $\boldsymbol{EL}(ld, a, b, e)$
- sets of types of vehicles identified for variants of the supply chain $\boldsymbol{STZ}(ld)$,
- sets of types of vehicles $\boldsymbol{STZV}(v, ld)$, sets of types of internal transport mode $\boldsymbol{STWV}(v, ld)$ for variants of the supply chain and their cells,
- sets of numbers of types of material goods supported by variants of the supply chain configuration, $\boldsymbol{H}(ld)$, $ld \in \boldsymbol{LD}$,
- the length of the connection between cells of the supply chain in particular variants of its configuration, $\ell(ld,(v,v'))$, $ld \in \boldsymbol{LD}$, $(v, v') \in \boldsymbol{LF}(ld)$,
- a random variable, interpreting the temporary traffic flow load capacity of the connection between cells of the supply chain in particular variants of its configuration, $q_0(ld,(v,v'),t)$, $ld \in \boldsymbol{LD}$, $(v, v') \in \boldsymbol{LF}(ld)$ the average value of which is equal to $\overline{q_0}(ld,(v,v'),t)$
- the speed of vehicles in free movement between cells of the supply chain for variants of its configuration, $vs(st,ld,(v,v'))$, $ld \in \boldsymbol{LD}$, $st \in \boldsymbol{STZ}(ld)$, $(v, v') \in \boldsymbol{LF}(ld)$,
- the costs of vehicles using road connections between cells of the supply chain for variants of its configuration, $kd(st,ld,(v,v'))$, $ld \in \boldsymbol{LD}$, $st \in \boldsymbol{STZ}(ld)$, $(v, v') \in \boldsymbol{LF}(ld)$,
- fixed costs for the variants of the supply chain configuration, $K(ld)$, $ld \in \boldsymbol{LD}$,
- distances per unit $kl(ld,v,st)$ and the cost of the use of vehicles of particular types available to cells of the supply chain per unit $kh(ld,v,st)$, $ld \in \boldsymbol{LD}$, $v \in \boldsymbol{V}(ld)$, $st \in \boldsymbol{STZV}(v, ld)$,

- the cost of operating the internal transport mode of *st*-th type by *v*-th element of *ld*-th supply chain $kw(ld,v,st)$, $ld \in \boldsymbol{LD}$, $v \in V(ld)$, $st \in \boldsymbol{STZV}(v, ld)$,
- a set of time intervals $\boldsymbol{T} = \{t: t = 1, 2, ..., T\}$.

However, the decision variables refer to:

- the selection of the variant of the supply chain configuration, $x(ld)$, $ld \in \boldsymbol{LD}$,
- the times of vehicle involvement in handling cargo streams in the selected variants of the supply chain configuration, $y1(ld, st, (v, v'), v'', a, b, e, h)$, $ld \in \boldsymbol{LD}$, $v'' \in V(ld)$, $st \in \boldsymbol{STZV}(v'', ld)$, $(v, v') \in \boldsymbol{LF}(ld)$, $a \in \boldsymbol{A}(ld)$, $b \in \boldsymbol{B}(ld)$, $e \in \boldsymbol{E}(ld, a, b)$, $h \in \boldsymbol{H}(ld)$,
- the times of involvement of means of transshipment in handling cargo streams in the selected variant of the chain configuration, $y2(ld, st, v, h)$, $ld \in \boldsymbol{LD}$, $v \in V(ld)$, $st \in \boldsymbol{STWV}(v, ld)$, $h \in \boldsymbol{H}(ld)$,
- the number of journeys of unloaded vehicles between cells of the supply chain in the selected variant of the configuration, $zp1(ld,st,(v,v'),v'')$, $ld \in \boldsymbol{LD}$, $v'' \in V(ld)$, $st \in \boldsymbol{STZ}(ld)$, $(v, v') \in \boldsymbol{LF}(ld)$,

In the developed model, taking into consideration the data described above, the values of the above decision variables should be determined in order to meet the constraints concerning:

- the selection of the supply chain structure as well as transport and storage routes,
- ensuring that the total working time of the vehicles is not longer than the available time,
- the use of the working time of the transport means,
- ensuring that the time obtained for the provision of logistics services will be accepted by the participants in the supply chain, which entails the selection of an appropriate technological route for each relation and the selection of technical means which will ensure that the provision of logistics services in this relation will not exceed the time expected by the participants in the supply chain,

and that the function of the criterion on the interpretation of the flow costs (formula (2)) and/or the function of the criterion on the interpretation of the probability of time losses (formula (4)) adopts minimum values:

$$WKC(ld) = K(ld)\cdot x(ld) + \sum_{st\in \boldsymbol{STZ}(ld)} \sum_{(v,v')\in \boldsymbol{LF}(ld)} \sum_{v''\in \boldsymbol{V}(ld)} \Bigg[\big(zl1(ld,st,(v,v'),v'') + zp1(ld,st(v,v'),v'')\big)\cdot \left(kd(st,ld,(v,v')) + \ell(ld,(v,v'))\cdot kl(ld,v'',st) + \frac{\ell(ld,(v,v'))}{vs(st,ld,(v,v'))}\cdot kh(ld,v'',st) \right) \Bigg] + \sum_{v\in \boldsymbol{V}(ld)} \sum_{st\in \boldsymbol{STWV}(v,ld)} \left[kw(ld,v,st)\cdot \sum_{h\in \boldsymbol{H}(ld)} y2(ld,st,v,h) \right] \xrightarrow[ld\in \boldsymbol{LD}]{} \min \quad (2)$$

where $zl1(ld,st,(v,v'),v'')$ is the number of loaded journeys determined as follows:

$$\forall ld \in \boldsymbol{LD} \ \ \forall v'' \in \boldsymbol{V}(ld) \ \ \forall st \in \boldsymbol{STZV}(v'',ld) \ \ \forall (v,v') \in \boldsymbol{LF}(ld)$$

$$zl1(ld,st,(v,v'),v'') = \frac{vs(st,ld,(v,v'))}{\ell(ld,(v,v'))}\cdot \sum_{h\in \boldsymbol{H}(ld)} \sum_{a\in \boldsymbol{A}(ld)} \sum_{b\in \boldsymbol{B}(ld)} \sum_{e\in \boldsymbol{E}(ld,a,b):(v,v')\in \boldsymbol{EL}(ld,a,b,e)} y1\big(ld,st,(v,v'),v'',a,b,e,h\big) \quad (3)$$

$$\mathrm{R}(\mathrm{ld}) = \mathrm{P}\big(\Delta \mathrm{T}(\mathrm{ld}) \le \mathrm{t_g}\big) \xrightarrow[\mathrm{ld}\in \mathbf{LD}]{} \max \quad (4)$$

where t_g is the permissible value of losses of time to be considered in technological routes, and $\Delta T(ld)$ is the actual value of losses in physical stream flows for *ld*-th variant of the supply chain configuration calculated as follows:

$$\forall ld \in \boldsymbol{LD} \quad \Delta T(ld) = \sum_{h\in \boldsymbol{H}(ld)} \sum_{v\in \boldsymbol{V}(ld)} \sum_{st\in \boldsymbol{STWV}(v,ld)} \left[\mathrm{sgn}\big(y2(ld,st,v,h)\big) \int_{t=0}^{T} \omega 2(ld,st,v,h,t)\ dt \right] + \sum_{h\in \boldsymbol{H}(ld)} \sum_{a\in \boldsymbol{A}(ld)} \sum_{b\in \boldsymbol{B}(ld)} \sum_{e\in \boldsymbol{E}(ld,a,b)} \sum_{v\in \boldsymbol{V}(ld)} \sum_{st\in \boldsymbol{STZV}(v,ld)} \sum_{(v',v'')\in \boldsymbol{EL}(ld,a,b,e)} \left[\mathrm{sgn}\big(y1(ld,st,(v',v''),v,a,b,e,h)\big)\cdot \int_{t=0}^{T} \omega 1(ld,st,(v',v''),v,a,b,e,h,t)\ dt \right] \quad (5)$$

where $\omega 2(ld,st,v,h,t)$ is a function mapping the time losses of the internal transport means of *st*-th type when handling material goods of *h*-th type in *v*-th cell of the supply chain for *ld*-th variant of its configuration, and $\omega 1(ld,st,(v',v''),v,a,b,e,h,t)$ is a function mapping the time losses of transport means of *st*-th type, which are at the disposal of *v*-th cell of the supply chain, when handling material goods of *h*-th type on *(v', v'')* connection between cells in the supply chain constituting an element of *e*-th route distinguished between *a*-th and *b*-th cell of the supply chain for *ld*-th variant of its configuration.

Time losses in flows of material goods are one of the most important measures for assessing the performance of logistics tasks in supply chains from the reliability point of view. These losses arise as a result of conflict situations occurring during the performance of logistics processes. In the proposed approach, they are identified with the use of simulation methods, because in practice time losses in individual elements of the supply chain result from decisions concerning the selection of technological paths and the selection of resources for their implementation, as well as from a number of other random events.

Additionally, the form of functions mapping time losses is strongly dependent on the type of these elements and their detailed parameters. For example, in road traffic models many analytical forms of functions are used which represent the extension of driving time due to the intensity of road traffic, while the identification and parameterisation of these functions in relation to particular sections of the transport network requires in-depth research. As an example, one may indicate here, quite often used in practice, the BPR2 function in the following form:

$$\mathrm{T}((\mathrm{v},\mathrm{v}'),\mathrm{t}) = \mathrm{T_0}(\mathrm{v},\mathrm{v}') + \begin{cases} \alpha(\mathrm{v},\mathrm{v}')\cdot \mathrm{T_0}(\mathrm{v},\mathrm{v}')\cdot \left(\dfrac{\mathrm{q}((\mathrm{v},\mathrm{v}'),\mathrm{t})}{\mathrm{c}(\mathrm{v},\mathrm{v}')\cdot \mathrm{q_{max}}(\mathrm{v},\mathrm{v}')} \right)^{\beta(\mathrm{v},\mathrm{v}')}, & \text{if } \mathrm{q}((\mathrm{v},\mathrm{v}'),\mathrm{t}) < \mathrm{c}(\mathrm{v},\mathrm{v}')\cdot \mathrm{q_{max}}(\mathrm{v},\mathrm{v}') \\ \alpha(\mathrm{v},\mathrm{v}')\cdot \mathrm{T_0}(\mathrm{v},\mathrm{v}')\cdot \left(\dfrac{\mathrm{q}((\mathrm{v},\mathrm{v}'),\mathrm{t})}{\mathrm{c}(\mathrm{v},\mathrm{v}')\cdot \mathrm{q_{max}}(\mathrm{v},\mathrm{v}')} \right)^{\beta'(\mathrm{v},\mathrm{v}')}, & \text{contrary} \end{cases} \quad (6)$$

where $T((v, v'), t)$ is characteristic for the t moment actual journey time of the connection (v, v'), min, $T_0(v, v')$ – the journey time of the connection (v, v') in free movement (for $q((v, v'), t) = 0$), min, $q((v, v'), t)$ – identified for the t moment of the traffic flow on the connection (v, v'), veh/h, $q_{max}(v, v')$ – infrastructure capacity of the connection (v, v'), veh/h, $c(v, v')$ – a coefficient determining the part of the infrastructure capacity of the connection (v, v') characteristic for the level of freedom of movement C, while $\alpha(v, v')$, $\beta(v, v')$, $\beta'(v, v')$ are empirically determined parameters of the model for the connection (v, v').

At the same time, it should be noted that the load capacity on the transport network sections considered here results from the decision on the configuration of a given supply chain and, above all, from the existing distribution of traffic flows in a given transport network, which is a random phenomenon. As a consequence, the identification of the function mapping time losses and their parameters must be performed individually for each element of a given logistics network. On the other hand, the load capacities of elements taken into account in the calculation of service time extension, which result from logistics processes other than those analysed, may be assumed as average values characteristic for a given moment (time of day), or drawn according to an identified probability distribution, which describes this phenomenon.

The above conditions cause that the value of the function $R(ld)$ is determined on the basis of an empirical distribution obtained experimentally, taking into account the randomness of the state of elements of the logistics system.

The reliability of the supply chain may also be considered from the point of view of the reliability of the tasks performed. In this respect, the reliability indicators for the transport means and load equipment and the category of human work should also be taken into account. Owing to this, by assigning the most reliable resources to the most reliable production lines, it is possible to guarantee the effective performance of logistics tasks in the supply chain.

4. Reliability evaluation algorithm for performance of logistics tasks

In order to assess the reliability of the supply chain due to the probability of excessive time losses in the performance of logistics tasks, which depend on random situations occurring during transport, handling operations and other transformations made in the supply chain in physical streams, an algorithm was developed to determine the distribution of sums of time losses in the flow of material goods and the probability that time losses will not be greater than permissible. The article presents a simplified form of this algorithm taking into consideration one variant of the supply chain configuration and one relation of displacement of material goods within one route, as well as one type of cargo.

For the purpose of developing the algorithm for determining the probability of exceeding the permissible time losses, an *ex* designation was introduced to interpret the number of the simulation experiment and *EX* to interpret the number of these experiments.

The steps of the developed algorithm may be presented as follows:

Step 1. Enter the input data including, among others: ***LD***, ***V***(*ld*), ***A***(*ld*), ***B***(*ld*), ***E***(*ld*, *a*, *b*), ***STZ***(*ld*), ***STW***(*ld*) ***H***(*ld*), as well as variants of logistics processes (technological routes and means of work and employees assigned to their performance).

Step 2. Experiment number *ex* := 1;

Step 3. Simulation mapping of disturbances for the current experiment (*ex*) related to, among others, uncertainty of orders and malfunction of means of work, as well as the current load capacity of elements of the logistics system.

Step 4. Development of schedules for the current experiment (*ex*) for the performance of material goods flow processes, taking into account time losses resulting from disturbances and the resulting conflict situations. For this purpose, the moment of flow initiation and its subsequent stages are taken into account.

Step 5. Determination of the amount of losses in the flows of physical streams for the current experiment (*ex*) and for individual variants of the supply chain configuration $ld \in \boldsymbol{LD}$ according to the relation (5).

Step 6. Is *ex* = *EX*?
NO: Assume *ex* := *ex* + 1 and go to step 3.
YES: Go to step 7.

Step 7. Determination of empirical distribution of average time losses in the flows of physical streams for individual variants of the supply chain configuration $ld \in \boldsymbol{LD}$.

Step 8. Determination of the value of the function of purpose (4) for particular variants of the supply chain configuration $ld \in \boldsymbol{LD}$.

Step 9. Comparison of variants of the supply chain configuration due to exceeding the permissible time losses in the flows of physical streams.

5. Practical application

Time losses on connections between cells of the supply chain and in its point elements were simulated using the algorithm described in the previous section. Therefore, additional disruptions and accumulations in the flows of physical streams as well as the current random load capacity on elements of the logistics network have been taken into consideration here. The simulation assumed that in cells of the supply chain and in linear elements time losses were described by an exponential distribution of individually determined parameters (lambda = 0.5). The probability of occurrence of time losses $R(ld)$ in the whole supply chain was determined as the product of probability in its particular elements (called partial probabilities in the simulation model) $R'(ld)$, because random events in particular objects of the supply chain are treated as randomly independent events. The distribution function of the exponential distribution, on the basis of which the probability of exceeding the permissible time losses was determined, is presented as:

$$P(X < T^{dop}) = 1 - e^{-\lambda T^{dop}} \tag{7}$$

The analysed supply chain consists of the following elements: suppliers {1, 2}, manufacturer {3}, distribution warehouse {4} and recipient {5}. The delivery of cargo from the manufacturer to the recipient may be carried out in two ways: directly in a relationship between the manufacturer – the recipient {(3, 5)} or indirectly through a distribution warehouse {(3, 4), (4, 5)}. – Fig. 1.

Taking into account the above and the two types of vehicles (with 16 and 33 pallet spaces), the following variants were considered in the simulation research of the flow of cargo streams in the supply chain:

- Variant. 1. More frequent direct deliveries in a relationship between the manufacturer – the recipient (smaller vehicles). The following limit values have been adopted for each element of the supply chain: suppliers {1} – 5 [min.], suppliers {2} – 4 [min.], manufacturer {3} – 7 [min.], distribution warehouse {4} – 6 [min.], recipient {5} – 4 [min.], all relationships on connections – 8 [min.]. More frequent deliveries impose the minimisation of permissible time losses in connection with a saturated production plan.
- Variant. 2. Intermediate deliveries in a relationship between the manufacturer – the distribution warehouse with larger vehicles (less frequent deliveries) and the distribution warehouse – the recipient with smaller vehicles (more frequent deliveries). The following limit values have been adopted for each element of the supply chain: suppliers {1} – 7 [min.], suppliers {2} – 8 [min.], manufacturer {3} – 7 [min.], distribution warehouse {4} – 8 [min.], recipient {5} – 4 [min.], connection (3,4) – 9 and (4,5) – 7 [min], other relationships 9 [min.]. Less frequent deliveries make it possible to increase the permissible time losses and result from a less saturated production plan.
- Variant. 3. Less frequent direct and indirect deliveries in a relationship between the manufacturer – the recipient (larger vehicles), delivery of material goods to the manufacturer with larger vehicles (less frequent deliveries), frequent deliveries to the

manufacturer. The following limit values have been adopted for each element of the supply chain: suppliers {1} – 5 [min.], suppliers {2} – 4 [min.], manufacturer {3} – 7 [min.], distribution warehouse {4} – 8 [min.], recipient {5} – 8 [min.], connection (3,5), (3,4) and (4,5) – 8, other relationships 5 [min.].

Source: own elaboration.

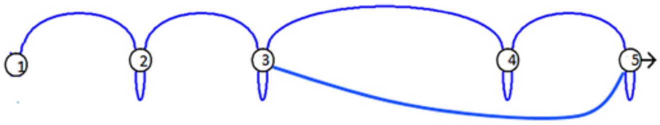

Fig. 1. Cells of the supply chain

In order to determine the probability of exceeding the permissible time losses *R*(*ld*) for the analysed variants, time *R'*(*ld*) chain have been taken into account according to empirical probability distributions. The results obtained for the three variants described above are presented in Table 1. Costs are indicators for the assessment of cargo flows in supply chains that do not determine time losses, thus they have been omitted from the analysis. Costs are the effect of time losses and are reflected in the financial settlements of the chain flow. Considering the results presented in Table 1, it may be concluded that the main factor affecting time losses in particular cells and on the linear elements of the logistics network is the frequency of cargo delivery. In the case of frequent deliveries, minimum time losses are required due to the timeliness of completion of particular tasks in the chain and maintaining the cargo flow. According to the assumed empirical distribution (i.e. exponential distribution), it may be stated that the frequency of deliveries negatively affects the probability of exceeding the permissible time losses in the analysed supply chains. In each element of the supply chain, increasing the time of permissible losses increases the likelihood of occurrence of such losses. The analysed variants present various combinations of permissible time losses in different elements depending on the frequency of deliveries. In variant 2, the requirements for minimising the losses in particular elements of the chain generated the highest probability of not exceeding these losses.

6. Summary

The article presents an approach to studying the reliability of logistics processes, taking into account the probability of exceeding the total time losses generated in point and linear elements of the supply chain. Time losses generated in the supply chain also depend to a large extent on traffic conditions, as well as accumulations in the flows of physical streams (especially in logistics facilities) and related delays. The simulation model considered time losses resulting from delays generated in linear and point elements of the supply chain, which are formed by suppliers, recipients and logistics facilities (e.g. transshipment points) and other entities occurring in physical flows of material goods.

Further research on the assessment of the reliability of logistics processes in terms of calculating of total time losses may be carried out by extending the mathematical model with additional random factors generating time losses, e.g. accidents, wrong route selection by drivers.

It should be stressed that taking time losses into consideration as a criterion for assessing the variants of the supply chain configuration is a response to the need to increase the efficiency of supply chains – especially in terms of minimising the operations not increasing the value of material goods.

Table 1. Results of simulation research on time losses in variants of the supply chain configuration and allocation of means of work

Supply chain element	**Partial likelihood of exceeding the permissible time losses** *R'*(*ld*)		
	Variant 1	Variant 2	Variant 3
Supplier of materials (1)	0.91	0.96	0.91
Supplier of semi-finished products (2)	0.86	0.98	0.86
Manufacturer (3)	0.96	0.96	0.96
Distribution warehouse (4)	0.95	0.91	0.98
Recipient (5)	0.86	0.86	0.98
Connection (1, 2)	0.98	0.98	0.91
Connection (2, 3)	0.98	0.98	0.91
Connection (3, 4)	0.98	0.98	0.98
Connection (4, 5)	0.98	0.96	0.98
Connection (3, 5)	0.98	0.98	0.98
Likelihood of exceeding the permissible time losses *R*(*ld*) for the variant	0.55	0.62	0.56

Source: own elaboration.

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