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SUPPLY CHAIN RELIABILITY MODELLING

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ABSTRACT. Background: Today it is virtually impossible to operate alone on the international level in the logistics business. This promotes the establishment and development of new integrated business entities - logistic operators. However, such cooperation within a supply chain creates also many problems related to the supply chain reliability as well as the optimization of the supplies planning.

The aim of this paper was to develop and formulate the mathematical model and algorithms to find the optimum plan of supplies by using economic criterion and the model for the probability evaluating of non-failure operation of supply chain.

Methods: The mathematical model and algorithms to find the optimum plan of supplies were developed and formulated by using economic criterion and the model for the probability evaluating of non-failure operation of supply chain.

Results and conclusions: The problem of ensuring failure-free performance of goods supply channel analyzed in the paper is characteristic of distributed network systems that make active use of business process outsourcing technologies. The complex planning problem occurring in such systems that requires taking into account the consumer's requirements for failure-free performance in terms of supply volumes and correctness can be reduced to a relatively simple linear programming problem through logical analysis of the structures. The sequence of the operations, which should be taken into account during the process of the supply planning with the supplier's functional reliability, was presented.

Key words: supply chain, optimization of planning, functional failure, structural reliability.

INTRODUCTION

Today it is virtually impossible to operate single-handedly on the international level in the logistics business. This promotes establishment and development of new integrated business entities - logistic operators who actively use business process outsourcing in supply management - in the global market for logistic services. The advantages of such outsourcing in supply chain (SC) management are obvious, and demand for this technology in the mature US and European markets is steadily growing. At the same time, efficiency of this technology largely depends on confidence and coordination in relations and operations of all supply chain partner companies. Economic vulnerability of such entities lies in the risk of SC disruptions at the boundaries of functional areas. Such disruptions cause breaches of contractual obligations related to supply timeliness (JIT - Just in Time), sequence (JIS - Just in Sequence) and completeness (capacity, JIC - Just in Capacity), and can be viewed as SC failures. The economic impact of such failures is usually substantial both for the focus company and for the partner companies. This is what makes transition from qualitative analysis of SC risks in the context of classic risk management to quantitative analysis based on the general systems reliability theory models and methods so relevant. The need for quantitative evaluation of SC risks has already been recognized by major logistic companies, manifesting itself in wider standardization of requirements for supply quality and reliability both for the purposes of attracting new customers and establishing specifications to be met by suppliers of goods and services (Tables 1, 2). Ensuring supply reliability is becoming one of the highest priorities in modern day logistics.

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Table 1. Service quality indicators
Tabela 1. Wskaźniki poziomu obsługi klienta

Indicator	**Value**	**Company**
Delivery timeliness	98 %	3M
Ideal order: Timeliness & Completeness & Payment	90 %	Procter&Gamble
Requirements for suppliers: just-in-time delivery	99.5 %	Philips Sem.
	98 %	Sequent Comp.
Perfect order: Correctness & Completeness & Accuracy	98 %	Hewlett-Packard
Guaranteed delivery time (UK)	days	RS Components
Total cost of supply process ownership (TCO): supplier ranking score	points	Sun Microsystems

Table 2. Supply quality and reliability requirements standardization practice
Tabela 2. Metody standaryzacji jakości dostaw i wiarygodności zapotrzebowań

Company	Risk factor	Factor value (permissible, planned, required)	Process reliability (failure-free performance)
Tesco (UK)	Permissible delay in delivery	0.5 h	0.985
	Order configuration correctness	0.5 %	0.995
Vision Express (UK)	Time taken to deliver the goods to the customer	1 h	0,95
Nissan (UK)	Number of defective (faulty) articles in the delivery	0.005 %	0.99995
Royal Mail (UK)	Probability of delivery within one day	-	0.9
Saturn	Permissible delay in delivery	0.25 h	-
Siemens EMS	Percentage of the supply plan accomplished by the established deadline	98 %	0.98

SUPPLY CHAIN FAILURE CONCEPT AND GENERAL APPROACH TO SUPPLY PLANNING

Failure is the key concept in the systems reliability theory. Let us assume that a SC failure means an event consisting in non-fulfilment of goods delivery obligations under any contract clause constituting a risk factor (time, volume etc.) due to a disruption in the SC. For our purposes, it is practical to view the SC from the process and operational standpoint rather than in the traditional object/function context (supplier, manufacturer, intermediary etc.). I.e. the supply chain should be analysed as a sequence of interconnected processes through which the focus company fulfils its contractual obligations related to delivery of goods from the supplier to the end consumer using the well-known 5-process SCOR model [15]. This approach to SC representation and analysis is fully consistent with the process control methodology and ABC (Active Base Costing) process-by-process costing technology. Besides, it allows clearly formalizing the task of providing supply channel redundancy based on the reliability requirements using the systems structural reliability theory models.

Let us consider a situation that can occur when the JIT (Just in Time) technology is implemented. Let us assume that deliveries are consolidated into one shipment. A functional failure is defined as an event where planned time t0 for the delivery of an order with the volume of Q_0 is exceeded. Let $F(t > t_0)$ be the probability of exceeding the planned time needed to process the entire order, and $P_0(t_0)$ - the specified probability of failure-free operation. To ensure this level of failure-free performance, we need to create a network of n channels by analysing the supplier market and evaluating their potential functional capabilities. The functional condition of failure-free operation of the *i*-th supply channel will be defined by the following expression:

$$t_i = \frac{Q_0}{\lambda_i} \le t_0,$$

where λ_i - potential supply rate through the i-th channel.

The above formula shows that two channel types can exist in the network: primary channels with the possible supply volume of $q_i = \lambda_i t_0 \ge Q_0$ and auxiliary channels that cannot handle the necessary supply volume within the planned time by themselves. Auxiliary channels can be combined into chains subject to the following condition:

$$t_j = \frac{Q_0}{\sum_j^k \lambda_j} \le t_0, \quad k < n.$$

A supply network with a serial-parallel structural reliability scheme is created from the primary channels and auxiliary channel chains. Optimal supply plan $\{Z_i\}^n$ is found by solving the following mathematical programming problem:

$$S = \sum_{i=1}^{n} C_i Z_i \to \min$$

subject to the following limitations:

$$\sum_{i=1}^{n} Z_i = Q_0, \quad 0 \le Z_i \le q_i \quad (i = \overline{1,n}), \quad P(t \le t_0) \ge P_0(t_0),$$

where:

C_i, q_i - cost price and possible volume (capacity) of supply through the *i*-th chain, respectively ($q_i = \lambda_i t_0$);

$P(t \le t_0)$ - failure-free performance of supply determined using the structural reliability model.

SUPPLY CHAIN PROCESS MODEL

The classic process model of SC management (Figure 1) based on the minimum cost criteria with independent processes and the specified failure-free performance requirement looks like the following:

$$S_\Sigma = \sum_{i=1}^{n} \sum_{j=1}^{m} S_{ij} X_{ij} \to \min \qquad (1)$$

subject to the following limitations:

$$\sum_{j=1}^{m} X_{ij} = 1, \qquad i = \overline{1,n};$$

$$\prod_{i=1}^{n} \sum_{j=1}^{m} P_{ij} X_{ij} \ge \beta;$$

where:

n – number of processes,

m = max $\{k_i\}_n$,

k_i - number of possible alternatives (strategies) for implementation of the ***i***-ith process,

S_{ij} – costs of the i-th process in the SC during implementation of the j-th strategy,

$\{S_{ij}\}_n^m$ - process cost matrix,

β – specified (required) SC failure-free performance (probability of failure-free SC operation),

P_{ij} – probability of failure-free implementation of the j-th strategy in the i-th process,

$\{P_{ij}\}_n^m$ - failure-free operation probability matrix,

X_{ij} – binary variable (selection variable) that takes the value of 0 or 1.

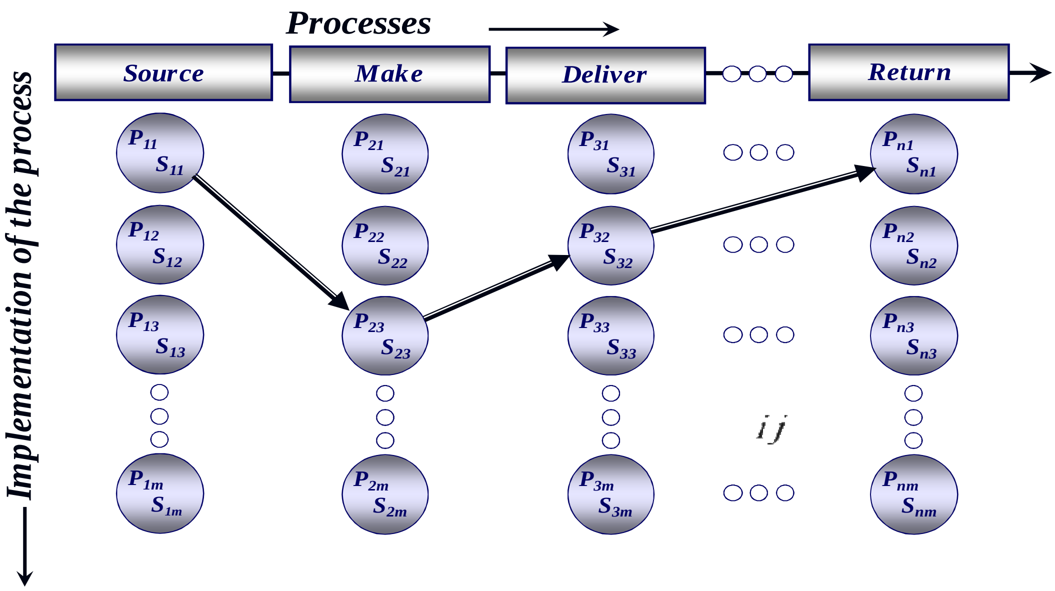

Fig. 1. Business process selection diagram
Rys. 1. Schemat procesu dokonywania wyboru

An additional limitation of individual process reliability in the SC can be introduced into the model:

$$\sum_{j=1}^{m} P_{ij} X_{ij} \geq \alpha_i, \qquad i = \overline{1,n};$$

where: $\{\alpha_i\}_1^n$ - process failure-free operation limitation vector ($i = \overline{1,n}$).

The solution is found as a non-vanishing vector from matrix $\{X_{ij}\}_n^m$.

Model (1) requires an excess of offers in the business process market, which is not always the case in practice. If it is impossible to select a set of processes that would ensure the required SC reliability, a model that allows maximizing the SC reliability within the given cost limitations can be used:

$$\prod_{i=1}^{n}\sum_{j=1}^{m} P_{ij} X_{ij} \rightarrow \max,$$

$$S_{\Sigma} = \sum_{i=1}^{n}\sum_{j=1}^{m} S_{ij} X_{ij} \le S_0, \quad \sum_{j=1}^{m} X_{ij} = 1, \qquad i = \overline{1,n};$$

where: S_0 - budget limitation.

STANDARDIZATION OF RELIABILITY REQUIREMENTS

The use of model (1) poses certain difficulties since statistical studies are necessary to obtain objective evaluations of matrix $\{P_{ij}\}_n^m$. At the same time, when designing the SC, one needs to solve the problems of selecting service (i.e. process) providers based on the end consumer's supply reliability requirements β. In other words, the problem of standardizing failure-free process performance requirements emerges. Let us consider the algorithm of solving this problem, assuming that the processes are independent, and the failure flows are simple.

Based on the primary reliability equation, we obtain:

$$P(t_{\beta}) = \exp(-\lambda_0 t_{\beta}) = \beta, \tag{2}$$

therefore:

$$\lambda_0 = -\frac{\ln(\beta)}{t_{\beta}}, \tag{3}$$

where:
$\boldsymbol{\lambda_0}$ – SC failure flow rate;
$\boldsymbol{t_{\beta}}$ – risk factor value (time, volume etc.) at failure-free performance level β.

If there are no processes with dominant failure rates in the SC, we can assume that:

$$\lambda_{ij} = \lambda_0 \omega_{ij}, \tag{4}$$

where:

$\boldsymbol{\lambda_{ij}}$ – ***i***-th process failure rate under the ***j***-th implementation strategy,
$\boldsymbol{\omega_{ij}}$ – weight factor of the contribution of the ***j***-th strategy of the ***i***-th process to the total SC failure rate.

Taking into account (2), we obtain:

$$P_{ij} = \exp(-\lambda_0 \omega_{ij} t_{\beta}) = \exp[\omega_{ij} \ln(\beta)]. \tag{5}$$

The only thing left is to define weight factor matrix $\{\omega_{ij}\}_n^m$. Obviously, the more damage a failure of a particular process can cause, the higher the reliability requirements for that process should be. Damage can be measured in process recovery costs, losses in sale of goods etc. For example, costs can be assessed through turnover and tariff losses using the following formula:

$$R = Qd[1-(1-\frac{\delta}{100})(1-\frac{\varepsilon}{100})],$$

where:
Q – turnover,
d – sale price,
δ, ε – turnover and price losses in %, respectively.

In this case, weight factors are inversely related to costs and are calculated according to the following formula:

$$\omega_{ij} = \frac{1}{R_{ij} \sum_{i=1}^{n} \frac{1}{R_{ij}}}, \tag{6}$$

where R_{ij} – costs related to failure in implementation of the ***j***-th strategy of the ***i***-th process.

GENERALIZED OUTSOURCING SUPPLY PLANNING MODEL

Ensuring the required failure-free performance in SCOR-type supply chain process models involves the need to provide supply chain redundancy. Let us consider a situation that can occur when the JIT technology is implemented. Let us assume that deliveries are consolidated into one shipment. A functional failure is defined as an event where planned time t_0 for the delivery of an order with the volume of Q_0 is exceeded. Let $F(t>t_0)$ be the probability of exceeding the planned time needed to process the entire order, and $P_0(t_0)$ - the specified probability of failure-free operation. To ensure this level of failure-free performance, we need to create a network of *n* channels by analysing the supplier market and evaluating their potential functional capabilities. Let us assume that reliability requirement $P_0(t_0) = \varphi(p_1, p_2,...., p_n) \geq P_2^*$ (where $\varphi(p_1, p_2,...., p_n)$ - function determined by the structural reliability scheme (redundancy scheme); P_2^* - end consumer's supply reliability requirements) had been determined as a result of solving the standardization problem and has been agreed upon with the responsible supplier or supply operator (level 1 supplier). If the responsible supplier is unable to meet the contractual terms by itself, it creates a network of level 2 suppliers based on outsourcing principles. Those suppliers can, in turn, build level 3, 4 etc. networks based on the same principles. In this supply network failures mean independent events consisting in non-fulfilment of contractual obligations by one or several functional parameters - such as time, sequence, completeness or volume of supply.

Since a supply network can be made up of channels with different characteristics, the network structural reliability model will, in general, include both channels consisting of individual suppliers and supply chains or even entire sub-networks with a relatively complex (fractal) structure (Figure 2).

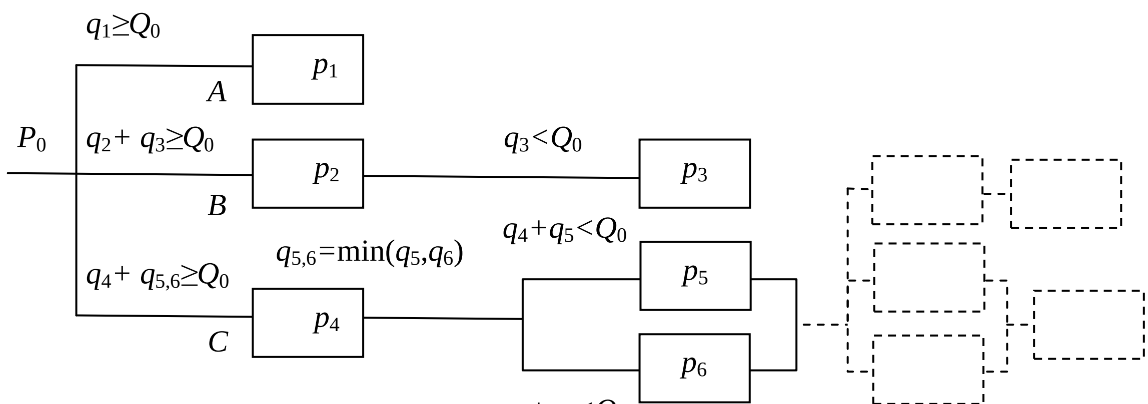

Fig. 2. Multi-level supply network structural reliability model
Rys. 2. Wielopoziomowy model wiarygodności łańcucha dostaw

For the customer, the problem of building a supply network turns into the problem of selecting the most economically sound channels that meet the requirements for functional parameters (such as volume) and failure-free performance determined using the formula for the simple serial-parallel scheme:

$$P_0 = 1 - \prod_{i=1}^{m} (1 - \prod_{j=1}^{n} p_j)_i,\ m \le n,\ if\ x_{i,j}\ not\ 0,$$

where:
n – number of suppliers,
m – number of supply chains (channels),
$x_{i,j}$ – binary variable (selection variable) that takes the value of 1 if the capacity of j suppliers included in the i-th supply channel allows meeting demand $\sum_{j=1}^{n} q_j x_{i,j} \ge Q_0$ or the value of 0 – if not, i.e. $\sum_{j=1}^{n} q_j x_{i,j} < Q_0$. The binary variable is used to create m chains from n channels.

In a particular case where n = m the supply network structural reliability model consists of n channels with the capacity of $q_i \ge Q_0$ connected in parallel.

Therefore, it is suggested to use the logical-and-probabilistic analysis method to create multi-level supply network models with a complex structure.

CONCLUSIONS

The problem of ensuring failure-free performance of goods supply channel analysed above is characteristic of distributed network systems that make active use of business process outsourcing technologies. An essential condition is the availability of a mature logistic service market and intense competition in the market for business processes. The multi-level outsourcing model structure can be similar to that of a finite fractal. The complex planning problem occurring in such systems that requires taking into account the consumer's requirements for failure-free performance in terms of supply volumes and correctness can be reduced to a relatively simple linear programming problem through logical analysis of the structures. In general, to summarize the approach described in this article, supply planning with the supplier's functional reliability taken into account can be represented as a sequence of the following operations:

- Building a functional diagram of the network, with specification of all level 2 suppliers and their characteristics.
- Defining the failure concept and establishing the suppliers' functional capabilities criteria values based on the customer's requirements.
- Creating a serial-parallel scheme and a structural reliability calculation model based on the failure-free performance requirements and the supplier's functional capabilities.
- Determining the optimum supply plan that keeps the costs to the minimum while meeting the failure-free performance requirements.

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MODELOWANIE WIARYGODNOŚCI ŁAŃCUCHA DOSTAW

STRESZCZENIE. **Wstęp**: Obecnie nie jest możliwym prowadzenie działalności logistycznej o zasięgu międzynarodowym bez współpracy z innymi partnerami. Fakt ten doprowadził do powstawania i rozwoju nowych struktur organizacyjnych - operatorów logistycznych. Jednak taki typ współpracy w obrębie łańcucha dostaw stwarza możliwość występowania wielu problemów związanych z wiarygodnością tego łańcucha oraz optymalizacją planowania dostaw.
Celem pracy było opracowania matematycznego modelu dla znalezienia optymalnego planu dostaw przy zastosowaniu kryteriów ekonomicznych oraz modelu prawdopodobieństwa niezawodności łańcucha dostaw.
Metody: Model matematyczny oraz algorytmy wyznaczające optymalny plan dostaw został opracowany i sformułowany poprzez zastosowanie kryteriów ekonomicznych oraz modelu prawdopodobieństwa niezawodności łańcucha dostaw.
Wyniki i wnioski: Problem niezawodności łańcucha dostaw, który został poddany analizie w pracy, występuje często w sieciowych systemach dystrybucyjnych, stosujących metodę outsourcingu. Problem planowania występujący w takich systemach, które muszą uwzględniać wymagania klientów dotyczące niezawodności dostaw, może być zredukowany do relatywnie prostego zagadnienia programowania liniowego poprzez logiczną analizę struktur. Przedstawiono sekwencję operacji, które należy wziąć pod uwagę w procesie planowania dostaw przy uwzględnianiu funkcjonalnej wiarygodności.

Słowa kluczowe: łańcuch dostaw, optymalizacja planowania, porażka funkcjonalna, wiarygodność strukturalna.

MODELLIERUNG VON ZUVERLÄSSIGKEIT EINER LIEFERKETTE

ZUSAMMENFASSUNG. Einleitung: Es besteht heutzutage keine Möglichkeit mehr, eine logistische Aktivität von internationaler Reichweite ohne Zusammenarbeit mit anderen Partnern zu betätigen. Diese Tatsache führte zur Entstehung und Entwicklung von neuen Organisationsstrukturen - d. h. Logistik-Operateuren. Ein solcher Typ der Zusammenarbeit innerhalb einer Lieferkette generiert jedoch bestimmte Gefahren hinsichtlich der Glaubwürdigkeit und Zuverlässigkeit jeweiliger Lieferketten sowie hinsichtlich der Optimierung der Planung von Anlieferungen.
Das Ziel der Arbeit war es, ein mathematisches Modell für die Erstellung eines optimalen Zeitplans für Anlieferungen unter Benutzung von wirtschaftlichen Kriterien und des Modells der Wahrscheinlichkeit der Zuverlässigkeit einer Lieferkette auszuarbeiten.

Methoden: Das mathematische Modell und die den optimalen Anlieferungsplan bestimmenden Algorithmen wurden unter Benutzung von wirtschaftlichen Kriterien und des Modells der Wahrscheinlichkeit der Zuverlässigkeit der betrachteten Lieferkette konzipiert und effektiv formuliert.

Ergebnisse und Fazit: Die Frage der Zuverlässigkeit der in der Studie analysierten Lieferkette tritt oft innerhalb der Netzwerk-Distributionssysteme, welche die Outsourcing-Methode anwenden, auf. Das dabei in solchen, die Kundenanforderungen hinsichtlich der Lieferzuverlässigkeit zu berücksichtigenden Systemen auftretende Problem der Zeitplanung kann zur einer relativ einfachen Frage der linienmäßigen Planung bei Inanspruchnahme einer logischen Analyse von Strukturen reduziert werden. Es wurde eine Operationssequenz dargestellt, welche man im Prozess der Lieferplanung bei Berücksichtigung der funktionstüchtigen Zuverlässigkeit der Lieferkette in Betracht ziehen muss..

Codewörter: Lieferkette, Optimierung der Planung, funktionsmäßiger Ausfall, strukturelle Zuverlässigkeit.

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