

## The synthesis model as a planning tool for effective supply chains resistant to adverse events

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### Highlights

- Planning modular supply chains enables them to be adapted to flexible innovative transformation.
- The method of synthesis is the basic tool for creating an effective and reliable sequence of modules.
- The modular supply chain synthesis should be a continuous and uniform process.
- The synergy effect can measure the effectiveness of designing modular, reliable supply chains.

### Abstract

The article presents the problem of planning effective modular supply chains to resist adverse events. The lack of effective models for planning such supply chains based on the synergy of individual links widens the knowledge gap in this area. The analyses confirm the legitimacy of forming effective and reliable supply chains ready for fitting supplies to specific orders, adaptation to flexible and innovative transformations, and minimization of time losses and costs of restoring supply capacity in case of a threat. The authors provide a theoretical analysis of the problem and present a proprietary approach to constructing reliable modular supply chains in the automotive industry. It has been shown that the synergy effect can measure the effectiveness of the design of such chains. A proprietary synthesis model was presented. The model can serve as a tool to support the planning of modular supply chains that are resistant to adverse events.

### Keywords

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synthesis model, structural-functional module, supply chains effectiveness, process reliability.

## 1. Introduction

Since the beginning of the customer era, logistics operators or service companies operating in different areas or regions have to be more and more flexible in adapting to the requirements of customers and the changing market requirements [9, 46, 66]. The most visible changes relate to the modern automotive economy. They include increasingly differentiated rules for the operation of the new car production industry and the after-sales service of end-of-life vehicles for maintenance and repair [25].

This requires companies to offer an extended range of services, complicating the process of constructing supply chains, increasing costs, and determining the emergence of new threats to the smooth supply of spare parts and accessories, particularly in the automotive aftermarket [27]. As many studies show, the possibility of undesirable events in supply chains is associated with vulnerability to threats, disruptions or uncertainty, and in some cases, with the security of the supply chain [1, 16, 17].

In response to these challenges, networks of cooperating carriers, logistic centres, warehouses and loading points [26, 57, 30] are being created. On the European transport services market, more than 60% of participants in such networks are classified in the segment of small and medium-sized enterprises - SMEs [5]. This is because big market players can provide the supplies of the ordered goods on their own. At the same time, smaller enterprises are forced to look for orders

supplementing the regular activities to increase their profitability [2], including services related to fleet management [54]. For these companies, cooperation in the service market becomes a strategic necessity to obtain financial flow through.

Research [20] shows that SMEs manage many different and interconnected relationships throughout the supply chain. Whereas [13] Faisal et al., by researching three Indian clusters of SMEs, indicated that managing risk in the supply chain requires a large exchange of information, close relationships and partners, and the adjustment of incentives and knowledge about the risk.

This article highlights the fundamental difference in procurement processes in the automotive market in the case of:

- fulfilment of procurement as an integral part of the production process; to mitigate the effects of a collapse in the supply chain, the use of factory stocks of auto parts is planned,
- realization of supplies in the service segment of the automotive market; with this approach, neither service centres nor car workshops create significant stocks of spare parts, which forces service companies to become highly flexible in the supply of parts and to quickly restore the supply capacity of chains in the event of a breakdown in supply.

According to the authors, meeting the requirements of flexibility and quick restoration of the supply chain's capacity is possible when

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adopting a modular approach to create such a structure of supply chains. It allows contractors to:

- quick design of effective and reliable supply chains of spare parts and accessories tailored to specific orders,
- adaptation of supply chains to their flexible innovative transformations,
- minimizing the loss of time and costs of restoring the supply chain's resourcing capacity in emergencies.

Such an approach requires the development of unified modules both in the organizational and communication sphere and information interfaces of individual participants of the entire process. Considering the above, this article presents the concept model of planning effective and reliable modular supply chains resistant to adverse events and indicates the most important applications. The proposed approach combines many aspects: constructing the supply chains of spare parts and accessories adapted to specific orders, adapting supply chains to their flexible innovative transformations, and minimizing the loss of time and costs of restoring supply capacity in the event of a threat. The results obtained from the model can be used to support decision-making in planning modular supply chains resistant to adverse events based on various goals, such as lowering the cost of completing tasks, risk of fulfilling orders, etc.

Following the presented research methodology, the article's structure was planned as follows. Section 2 presents the theoretical background of the analysed problem and a literature review in the field of risk-based supply chain design. It also indicated a proprietary approach to constructing supply chains in the automotive industry. Section 3 describes the decision problems involved in designing supply chains for spare parts and accessories. The general mathematical formulation of the model and the procedure are presented in section 4. Section 5 describes the results of the case study of modular supply chain planning. In contrast, section 6 of the article discusses the challenges and possibilities of using the proposed approach in economic practice.

## 2. Literature review

The analysis of the literature on the subject allows us to state that the construction of supply chains can be carried out using both the integration approach [67] and the modular approach [7, 10]. The difference between these approaches is that the constructing process is based on maximum integrity in the first case. The second case is based on the rational selection of modules as components of supply chains. As shown in Figure 1, an unreliable supplier can be replaced at the request of the customer to reverse the supply chain's capacity quickly.

According to Clark and Baldwin [7], modularity should be seen as a concept based on interdependence between modules included in the supply chain and independence between modules not included in this chain. In addition, it was emphasized that when using a modular approach, attention should be paid to the fact that:

- isolating business activity as a certain structure-function module is a kind of abstraction because full business independence is not possible,
- there is a phenomenon of hiding information, which is defined in the literature as information asymmetry, which makes it difficult to select appropriate modules,
- the unification of interfaces should be carried out to connect modules while constructing the supply chains quickly.

As Jacyna-Gołda I. [31] points out, all elements (links)  $v, v'$  belonging to the  $ld$ -th ( $v, v' \in V(ld), ld \in LD$ ) of the chain must meet their separate performance expectations. This means that its components can be treated as a reliability system for the entire series. The failure of one or more elements means a failure of the entire chain. Conversely, the reliability of individual elements of the supply chain means that it can meet performance expectations in all markets around it. Hence,

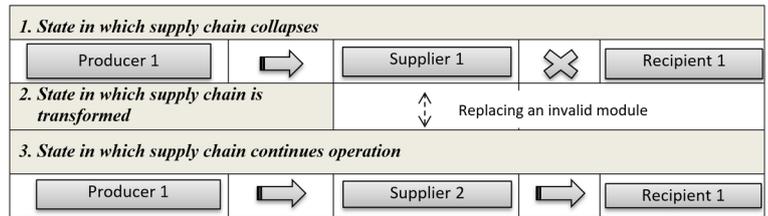


Fig. 1. Restoration of the supply chain's resupply capacity following an adverse event

for the entire supply chain, assuming that it has a serial structure, its  $VNS(ld)$  reliability in a structural sense can be determined as follows [29], [31]:

$$\forall ld \in LD \quad WNS(ld) = x(ld) \cdot \prod_{(v,v') \in L(ld)} nl(ld,(v,v')) \cdot \prod_{v \in V(ld)} mv(ld,v) \quad (1)$$

The most important factor determining effective supply chain management is credibility and trust in the relationships between the partners. Therefore, the key factors in achieving the sustainable success of enterprises and the development of each supply chain are increasing trust among partners and creating effective and reliable connections in the implementation of logistic tasks [34].

The authors of the paper argue that the only way to manage complex systems is to break them down into smaller pieces, then hide the complexity of each part behind an abstraction depicted as a module and introduce the links between modules - interfaces. In other words, modularization is the process of „... creating a complex product or service from smaller subsystems that can be designed independently but work together as a whole” [10]. Modularization is based on the concepts of “modular system” and “design using a modular approach.”

The modular system is a set of activities:

- related to the development of databases of discrete unified units to be used in the designs of various chains,
- related to the development of standard interfaces, and
- used to create a sequence of selected modules by connecting their interfaces to achieve the intended result.

Thus, designing using a modular approach constructs supply chains by selecting their components from a set of unified units with interfaces, hereinafter called modules, which can be independently created, modified, or exchanged between the designed chains.

An important problem in designing supply chains of spare parts and accessories is the right choice of connections between cooperating modules [50]. Much attention to this problem was devoted in publication [8]. On the other hand, Spring and Santos [56] categorize such connections, noting the difference between structural and procedural interfaces. Structured interfaces refer to the physical dimension of service modules, while procedural interfaces refer to the service provided by this module. Procedural interfaces focus on integrating the offer of services and relating to the service provider and the customer [45].

Another categorization was proposed in Van der Laan [60], who noticed the difference between functional and organizational interfaces. Functional interfaces combine modules' functions and affect the procurement task results. Organizational interfaces connect partners during delivery, including customers. Although many researchers point out that capturing the multidimensional and interdependent risk [17] and its dynamic nature [51] is necessary for designing supply chains. The individual modules are sensitive, vulnerable to threats and various disruptions and safety. Aspects related to the design of internal and external processes should also be taken into account [42].

Moreover, when designing supply chains in a modular approach, not only the risk assessment, the probability factor and the level of

impact are important aspects [63] but also the dependencies of the weak links that are related to:

- time, e.g. time delays, delivery time and delivery schedule [22, 48],
- functionally, e.g. stocks, production, products, transport [24, 64],
- relational, e.g. knowledge, social aspects, communication, suppliers and customers [3, 41].

For example, Nooraie and Parast [48] emphasized that identifying and eliminating many undesirable situations is possible long before reaching a critical state by modelling various scenarios. On the other hand, Heckmann I. in [22] presented a model built using the FTA (*Fault Tree Analyzes*) to analyse the symptoms of single threats in terms of timely deliveries.

Importantly, understanding supply chain risks promotes internal integration and strengthens alert capacities [53]. As the author points out, this enables enterprises to identify the risk associated with the supply chain in advance and shorten the obvious consequences or eliminate them.

Consumer perceptions of the risks associated with remanufactured products have been analysed by Wang et al. [61] using structural equation modelling on the example of the Chinese automotive spare parts industry. In the research, 288 respondents were tested to show that the perceived total risk was influenced by partial risks, such as physical risk, financial risk, time risk, resource risk, etc. As Ganguly [15] notes, the inability to integrate all relevant risks into the model can be problematic and potentially limits its effectiveness in categorizing supply chain risk and creating the risk assessment portfolio.

Similar studies with structural equation modelling were carried out by Yeh [63] and involved 851 suppliers of raw materials and spare parts for the Taiwanese automotive industry. In this case, the research results indicated a positive relationship between resources, trust, and commitment to supplier relationships and the electronic supply chain and a negative attitude to risk in case of electronic collaborative relationships. Similar studies were carried out by Wieland and Wallenburg [62] based on data collected from 270 respondents from three countries: Germany, Austria and Switzerland.

Identifying the risk in the supply chain is an ongoing process that may change over time. The potential risk may not be a future risk due to the development of new products or processes [67]. Therefore, we should strive to create system integration that will increase the visibility and transparency of risk throughout the entire supply chain [6, [33, 58].

Many studies in the last decade indicate the need to take into account the risk associated with the supply chain at the stage of its designing ([28, 37] or [44]) or the physical design of the supply chain [38]. The authors of the works [32, 35] discussed the relationship between contractors of tasks in the supply chain and the risk associated with it, e.g., the supplier-buyer relationship.

Frazzon E. M. et al. [14] drew attention to the fact that risk is related to costs. They use simulation and model oriented to minimize unplanned interruptions in the supply chain of car service stations and maintain their operating costs at an optimal level. They performed the simulations to improve procurement by optimizing logistic tasks in terms of economic and environmental efficiency.

Similarly, Ho C. et al. [23] built a model to assess the procurement cost depending on the effectiveness of the supply chain, which is implemented in the conditions of cooperation of various companies within the three-tier ERP (*Enterprise Resource Planning*) system. Deloitte Consulting approached the problem a bit differently [9]. They developed a model which uses information gathered through expert interviews, the experience of managers gained from organizing previous deliveries, and/or information collected through condition monitoring and historical databases. It was found that applied assumption causes a lack of flexibility in the information flows and

the incompleteness of the obtained results. Thus, it limits the proper assessment of the resilience of supply chains to risks.

On the other hand, Luksch S., [43] uses a model that considers the uncertainty resulting from the lack of complete and reliable information about inbound suppliers. However, it does not take into account random threats to individual links in the supply chain. He W. [21] approached the issue differently by using the model to develop forecasts ensuring safe goods stocks.

The analysis of the literature revealed several substantive gaps regarding:

- failure to take into account the various effects that arise during cooperation within supply chains,
- omitting the use of synthesis methods when constructing supply chains,
- no justification for the design of unique supply chains beyond the claim that such chains can be “perfectly” matched to specific procurement tasks. However, it should be emphasized that achieving ideal solutions is impossible because chains function in a changing environment.

When supplementing the above-mentioned substantive gaps, the authors focus, in particular, on the specificity of horizontal cooperation of suppliers. Particular attention has been paid to the SME segment due to its major share of the delivery services market in the economy of various regions. In the changing environment, service companies must develop such strategies for the performance of procurement that would correspond to their expanding scope. According to the authors, in most cases, such strategies enable avoiding adverse events. Therefore, the article proposes the use of:

- a modular approach taking into account the synergetic effects that arise during the cooperation of modules,
- synthesis methods as the basic tool for creating a sequence of modules,
- a multi-criteria evaluation model that considers the availability of a given module to resources and techniques reducing the manifestations of threats, the speed of its response to emergencies, and the minimization of costs for the performance of delivery tasks.

## 2. Knowledge acquisition as a stage of synthesis of the supply chains structures

### 2.1. Knowledge Mining

The effectiveness of the subcontractors' selection depends on the completeness of both the list of companies offering transport and logistics services and the information on their servicing capabilities. The analyses show that such information is not always consistent and reliable. To supplement the necessary information, it is proposed to use data exploration techniques (i.e., data mining) [49, 59], which were used for:

1. Anomaly detection,
2. Association rules,
3. Sorting of the search result.

The Apriori algorithm [4, 36] was chosen as the basic technique of knowledge mining. It detects combinations of logical events in data subgroups based on an “*if-then*” procedure, the application of which is based on the fact that:

- analysed information is sufficient because it brings together the basic number of companies offering their transport and logistics services,
- it is possible to divide the collected information into a small group of clusters.

For information processing, the authors adopted the following assumptions:

1. The database contains all the information on the most important transport and logistics market players.

2. The information space topology in the database is discrete. The values of the data parameters only take discrete values, which creates the basis for the decision to lock them into certain combinations of modules useful for achieving goals by the supply chain.
3. The gathered information is arranged as a square matrix and sufficient for successfully selecting 1st generation modules.
4. The selection process is carried out by referencing the combination of functional parameters of each module to the best values of such combinations characterizing the early selected modules.
5. The parameter sets of each of the selected 1st-generation modules can be used as the coordinates of the information space grid nodes of the structure of the designed supply chain. Such a mapping makes it possible to limit the number of further analysed module combinations.
6. Each selected 1st generation module should meet all requirements to create conditions for synergy effects during interaction with other modules.
7. The number of modules selected for subsequent analyses should be minimal but sufficient for implementing the transport and logistics task.

The recommendations regarding the advisability of using the analysed 1st-generation modules in the structure of the designed supply chain were developed during the research. Information instability creates gaps in the knowledge of decision-makers, increases their uncertainty and, consequently, becomes the cause of wrong decisions. This situation worsens due to the lack of certainty in the accuracy of the mathematical representation of transport and logistics activities, which creates premises for a low assessment of their credibility.

Supply chain activities are typically unique and cannot be accurately described by incomplete information gathered from past experiences. Various approaches to knowledge gathering are used to solve this problem, both with traditional planning methods (e.g., flexible planning, lean planning) and synthesis methods (in the sets of modules or in databases). To alleviate the above-mentioned difficulties, the authors introduced a two-stage procedure of knowledge mining useful in practical decision-making during for construction of supply chains (Figure 2).

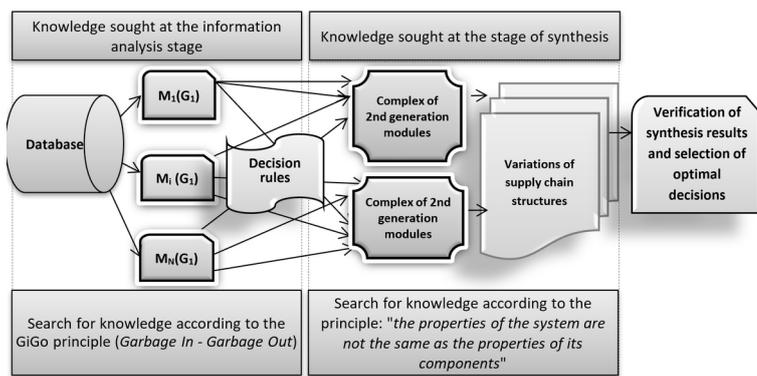


Fig. 2. The concept of a two-step search for knowledge in supply chain synthesis models

In line with this idea, the concepts of 2-generation modules have been introduced. Modules can be combined into stable two or three-module complexes to detect information about the chances of synergy effects in the case of their permanent cooperation.

## 2.2. Knowledge mining algorithm

A procedure for identifying 1st generation modules and their formation into a uniform complex was developed. The sequence of steps in selecting modules to be included in the chain structure is shown in

Figure 3, and its practical implementation was carried out using the Apriori algorithm [4, 36, 65].

At the first stage, the process of acquiring new knowledge is aimed at acquiring a set of 1st generation modules. The information collected in database is structured, and the participants of the service market (0-generation modules) are selected as hypothetically useful to perform tasks within the chain (set  $D[M(G_0)]$ ). Decisions about the capabilities of each 0-generation module (*Candidate Counting*) are based on the analysis of the parameters  $P_z = (p_0, \dots, p_n)$ , their efficiency ( $P_{iw}$ ) and resistance ( $P_{iod}$ ), Figure 3.

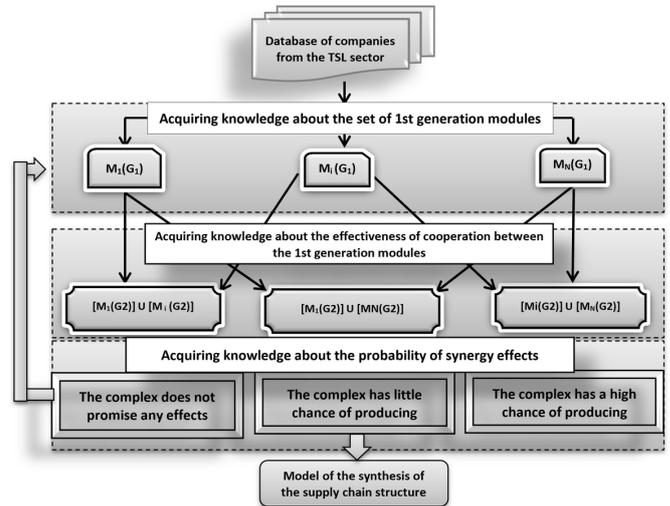


Fig. 3. Concept of the process of acquiring new knowledge in the supply chain synthesis model

A comparative assessment of the values of structural and functional parameters of modules with the minimum permissible values is performed. Then the set of 1st generation modules can be presented in the form:

$$[M_i(G_0)] \rightarrow D[M_i(G_1)], \text{ if } \{ \forall M_i(G_0) [(\sum P_{iw} \geq P_{wmin}) \& (\sum P_{iod} \geq P_{min})] \} \quad (2)$$

where:

$(P_{iw})$  – parameters of the  $i$ -modules of the 1st generation characterizing their performance,

$(P_{iod})$  – parameters of  $i$ -modules of the 1st generation resistant to threats.

The module selection process continues until the following condition is met:

$$D[M_i(G_1)] \geq N_s \quad (3)$$

where:

$M_i(G_0)$  – set of „Mi” modules with retrieved parameters,  $[M_i(G_0)] \in D[M_i(G_1)]$ ,

$N_s$  – number of executive modules included in the structure of the supply chain,  $s = 1 - S$ .

Modules selected for the 1st generation are sorted according to their performance and resilience levels. For this purpose, the weight value function is used (Table 1):

$$Wi = \frac{1}{2^{i-1}} \quad (4)$$

Unselected market participants are collected in the set  $D[M_j(G_0)]$ :

$$D[M_j(G_0)] \notin D[M_i(G_1)] \quad [5]$$

The acquired knowledge is subjected to assessing the accuracy of decisions made with Boolean algebras. If the module parameters  $M(G_0)[(P_{iw}), (P_{iod})]$  are below accepted level, then its inclusion in the next generation is a wrong decision:

$$M(G_0)[(P_{iw}), (P_{iod})] \rightarrow M_i(G_1) \subseteq [\text{set of wrong decisions}] \quad (6)$$

If the analysed module parameters  $M(G_0)[(P_{iw}), (P_{iod})]$  are above the accepted level, its inclusion in the next generation is the right decision:

$$M(G_0)[(P_{iw}), (P_{iod})] \rightarrow M_i(G_1) \subseteq [\text{set of good decisions}] \quad (7)$$

The condition for the completion of the decision validity process is to analyse all tested modules stored in the database:

$$D[M(G_0)] \supseteq \{D[M_j(G_0)] + D[M_i(G_1)]\} \quad [8]$$

At the second stage of the process of acquiring new knowledge, modules with indicator values at an acceptable level are included in the set of 2nd generation candidate modules. The rest of the modules are not considered further and remain in the database as candidates. The step is carried out using Boolean algebras and consists of the alternative:

*Case 1:* The required compatibility level  $(P_{ik})$  of the module  $[M_i(G_1)]$  is achieved:

$$[M_i(G_1)] \in D[M(G_2)], \text{ if } \{\forall M_i(G_1)[\sum P_{ik} \geq P_{kmin}]\} \quad (9)$$

*Case 2:* The required compatibility level  $(P_{ik})$  modulu  $[M_j(G_1)]$  is not achieved:

$$[M_j(G_1)] \notin D[M(G_2)], \text{ if } \{\forall M_i(G_1)[\sum P_{ik} \geq P_{kmin}]\} \quad (10)$$

The module files included and not included in the 2nd generation set include all or most of the 1st generation modules collected in the database:

$$D[M(G_1)] \supseteq \{[M_j(G_1)] \& D[M_i(G_2)]\} \quad [11]$$

At the third stage of acquiring knowledge, the sufficiency of the acquired modules is assessed. The sufficiency condition is the basic task in the synthesis of the supply chain structure. The lack of even one 2-generation module makes it impossible to build an integrated structure as incapable of providing the required transport and logistics services:

$$D[M_i(G_1)] \geq LM_{min} \quad (12)$$

where:

$M_i(G_1)$  – set of 1st generation modules,  $[M_i(G_1)] \in D[M_i(G_0)]$

$LM_{min}$  – the minimum number of modules needed to complete the tasks.

At the fourth stage of knowledge acquisition, the 1st generation modules, ordered according to performance and resistance parameters, are assessed according to the ability to cooperate (compatibility level  $P_k$ ).

$$P_k = \begin{cases} 0, & \text{in case of incompatibility;} \\ \in [0;1], & \text{in case of partial compatibility (e.g. geometric);} \\ 1, & \text{in case of full compatibility (ideal situation).} \end{cases} \quad (13)$$

Table 1. Weight index values

Analysed 0-generation modules		Absolute value	Relative value	Recommended decision
1	$[M_{i1}(G_0)]$	1,00	0,25	module is accepted into the basic list of 1st generation modules
2	$[M_{i2}(G_0)]$	1,00	0,25	module is accepted into the basic list of 1st generation modules
3	$[M_{i3}(G_0)]$	0,750	0,189	module is accepted into the additional list of 1st generation modules
4	$[M_{i4}(G_0)]$	0,500	0,126	module is accepted into the additional list of 1st generation modules
5	$[M_{i5}(G_0)]$	0,310	0,078	module is accepted conditionally
6	$[M_{i6}(G_0)]$	0,187	0,047	module is accepted conditionally
7	$[M_{i7}(G_0)]$	0,110	0,028	module is accepted conditionally
8	$[M_{i8}(G_0)]$	0,062	0,016	module is not accepted
9	$[M_{i9}(G_0)]$	0,035	0,009	module is not accepted
10	$[M_{i10}(G_0)]$	0,0195	0,005	module is not accepted

As most of the connections correspond to a situation of partial compatibility, all modules from the set  $D[M_i(G_1)]$ , are analysed, and the evaluation procedure is based on their compatibility indicators ( $WK$ ), which can be assessed as follows:

$$WK = 1 - \frac{N(L_k)}{\sum_s N_s} \quad (14)$$

where:

$N(L_k)$  – the number of links needed for the module to provide the required level of compatibility;

$N_s$  – the total number of links needed by the module to complete the assigned tasks.

The value of the compatibility index is variable within limits [0; 1]:

$$\left\{ \begin{array}{l} WK = 0, \text{ in case of } N(L_k) = \sum_i N_i \\ WK = 1, \text{ in case of } N(L_k) = 0 \end{array} \right. \quad [15]$$

The analysis shows that the greater the ability of a module to cooperate, the smaller number of links ensures their compatibility with other modules belonging to the supply chain structure. In addition to the links ensuring required compatibility, each module needs links to perform planned tasks. At this stage, the essence of the knowledge mining procedure is the analysis of events in which the module under consideration may take an active part while performing planned tasks. This ability is defined as „Support” by the analysed module of providing transport and logistics services in the supply chain.

The „Confidence” procedure verifies declared ability of the module to participate in the planned executive tasks actively. The procedure consists in assessing the probability that the module  $[M_i(G_2)]$  will be able to jointly perform the intended tasks together with the module  $[M_k(G_2)]$  already included in the supply chain structure. If the probability is above the required level, then the analysed module is included in the 2-generation set  $D[M_i(G_2)]$ .

The above analyses show that a given module  $[M_i(G_1)]$  has the support of  $W_s$ , if its cooperation with the module  $[M_k(G_2)]$  is effective in 95% of events predicted in the analysed period. Then:

$$SUPPORT[M_i(G_1)] \cup [M_k(G_2)] = (W_s)[M_i(G_1)] \cup [M_k(G_2)] \text{ for } ZT \geq 0,95 - 0,97 \quad [16]$$

$$CONFIDENCE[M_i(G_1)] \cup [M_k(G_2)] = P(W_s)[M_i(G_1)] \cup [M_k(G_2)] \quad [17]$$

At the fifth stage of acquiring new knowledge, a decision is made to use the procedure of supplementing the set of 2-generation modules (in case of a shortage of modules for the implementation of the chain tasks as a whole) or to proceed with the implementation of synthesis procedures (combining selected 2-generation modules into complexes containing two or three components).

Acquiring the knowledge gathered on the list of 1st-generation modules triggers acquiring knowledge about 2nd-generation modules, which, when cooperate, can be:

- combined into interlocked complexes, creating more efficient supply chains,
- excluded from the structure of the supply chain (lean supply chains),
- shifted in structure to increase the chain’s resistance to environmental changes.

### 3. Model of supply chain synthesis

#### 3.1. Model assumptions

The ability of the constructed supply chain to provide services depends on the number of subcontractors in its structure. The achievement of the appropriate size can be determined by the parameter CMI (*Critical Mass Index*). In our case, CMI indicates the minimum number of modules included in the chain so that the tasks included in the order are fulfilled and the costs incurred by subcontractors do not exceed the acceptable limits.

The authors of the article propose to focus on creating conditions for synergy effects after meeting these primary conditions. One of these conditions is the inclusion of technologically advanced subcontractors in the list of 2nd generation modules. The fulfilment of this condition is possible assuming that:

- any situation requiring changes in the supply chain structure is an opportunity to increase the quality of services by achieving the maximum level of synergy effects,
- in a situation of increased competition and new, unprecedented early requirements, the use of high-quality supply chains in logistics practice costs less than maintaining and repairing unreliable low-performance chains,
- the model of the synthesis of effective supply chains should include the morphological and structural-functional areas of the modelling of transport and logistics processes,
- the synthesis model is built based on the IDEF3 method, the main purpose of which is to visualize the sequence of processes performed on a set of selected 1st generation modules. The applied procedure is based on the assumed service provision scenario, where the supply chain is an ordered sequence of actions in the context of the performance of a service [39, 40],
- the solution to the problem of synthesis will be reliable if and only when, apart from solving the problems of morphological synthesis and structural synthesis, the third problem is solved - a combination of 1-generation modules in the structure of the supply chain that creates the basis for synergy effects as a result of their interaction.

#### 3.2. The concept of a synthesis model based on defined assumptions

For years, supply chain planning has been carried out using the method of sequential analysis of all possible solutions under a deterministic algorithm [55]. In practice, the number of options that must be analysed is so large, and the knowledge gaps are so deep that the continued use of such methods may fail in the entire process, and the credibility of the solutions becomes diminished.

If an effective variant of the supply chain structure is indicated, there is still a risk of low efficiency. High efficiency of the integrated supply chain is possible in the case of synergy effects (Figure 4).

Such effects result from the intra-chain cooperation of modules on the condition of their full structural and functional compatibility. The synergy effects are possible due to the right decisions during the supply chain synthesis forward and backward.

The fulfilment of this condition, reinforced by possessing at least one of the cooperating modules of innovative technologies, promises an increase in their efficiency and/or resistance to the manifestations of threats. According to the presented model, the knowledge about the supply chain structure becomes complete with the sequential introduction of new executive modules to this structure. Their implementation is based on information about relations between single modules arranged in a matrix, which creates the basis for completing multi-module complexes as links in the supply chain.

Each complex performs tasks on a specific supply chain section representing individual transport and logistics technologies. Therefore, in the process of synthesis, decisions result from answering the

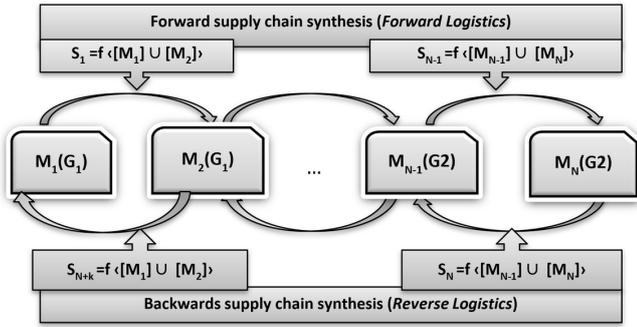


Fig. 4. The sequence of procedures for the synthesis of the supply chain structure in a closed-loop

questions “how” and “to whom and when” tangible goods mixed with in the supply chain will be transferred.

### 3.3. Conceptual problems of the synthesis model

The analysis of information sources indicates a number of difficulties in the formalization of the synthesis model of technical and logistic systems based on a set of components distinguished by local goals and local modes of operation [34], [52]. In the opinion of the authors, there are three difficulties arising from:

- Incompatibility of single models included in the supply chain structure. The authors’ analysis confirms that the compatibility is not a permanent feature of the modules, as the interoperability of the modules involved in different supply chains differ significantly. This is the result of different requirements for the services provided.
- Low credibility of the assumption that emergencies due to past threats are highly probable and future.
- Lack of certainty that the constructed supply chain will be as efficient and resilient as it was assumed during its design.

To alleviate the difficulties mentioned above, it was proposed to use the “Management and Coordination” subsystem (Figure 5). It eliminates the premises for the emergence of internal and external threats. Elimination of internal threats takes place by unifying the standards of links used by subcontractors. Elimination of external threats occurs by enhancing the overall resistance of the chain to threats as a result of the accumulation of individual resistances of each subcontractor involved.

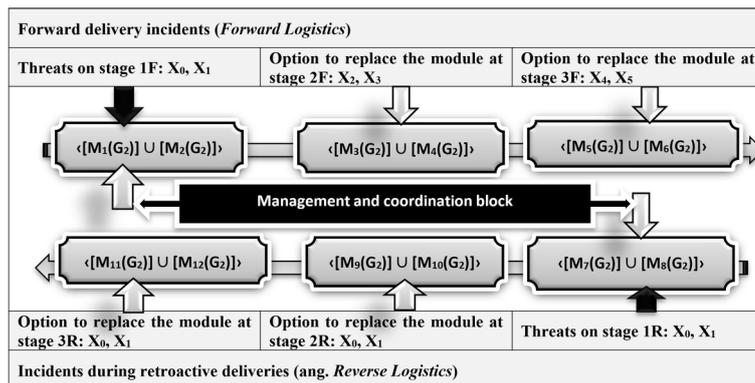


Fig. 5. The sequence of mechanisms for changing the executive modules

Secondly, to avoid difficulties resulting from the lack of reliable information on the effectiveness of cooperation of individual subcontractors in the future, the authors propose to use tools from the theory of probabilities in these studies. These tools allow for conclusions about the possible synergy effects in terms of potential opportunities.

### 3.4. Rules of structure synthesis vs set of events

The supply chain structure’s synthesis should be based on a set of 1st generation executive modules capable of cooperation within this chain and a set of links between these modules. To be successful in the synthesis process, the rules concerning a selection of appropriate modules and their combinations must be applied, i.e.:

- R1:** The decision to include the executive module  $[M_i]$  in the supply chain structure is made if this module can generate synergy effects. This ability is checked at each subsequent stage of synthesis.
- R2:** During the implementation of the executive modules, 4 procedures are used:
  - Duress*, according to which previously selected module  $[M_i]$  requires the selection of the module  $[M_{i+1}]$ .
  - Double duress*, whereby modules  $[M_i]$  and  $[M_{i+1}]$  are implemented together as a combined complex, creating a single link in the supply chain structure.
  - Need*, according to which the selection condition for the module  $[M_{i+1}]$  is the selection of the module  $[M_i]$ .
  - Prohibition of binary choices*, according to which two modules  $[M_i]$  and  $[M_{i+1}]$  cannot be implemented in parallel for one free position in the chain structure.
- R3:** If none of the 1st generation modules meets the requirements, the knowledge acquisition procedure should be restarted to search for the correct module on the list of 0th generation units.
- R4:** The choice of the interface of two cooperating modules must ensure their operation in which the probability of unplanned interruptions will be at an acceptable level.

In the proposed synthesis model, an event is understood as a set of input information ( $ZS_z$ ) and information about situations inside the chain ( $ZS_w$ ). Thus, the set of events can be represented as:

$$ZS = ZS_z(ZW + \Delta ZW, EZ + \Delta EZ) + ZS_w(WM + \Delta WM) \quad (18)$$

- The set of information on external events combines information about executive tasks ( $ZW$ ) and changes in these tasks ( $\Delta ZW$ ) and information about expected threats ( $EZ$ ) from the environment and unexpected threats ( $\Delta EZ$ ). These sets reflect various events outside the chain, including unplanned events causing re-scheduling of tasks, delivery delays, etc.
  - The set of internal events is a collection of information about activities planned during the cooperation of modules ( $WM$ ) and unplanned activities ( $\Delta WM$ ) caused by unexpected environmental threats. They have a decisive impact on changes in the states  $[SL_i]$  of the supply chain as a result of, for example, the formation of „bottlenecks” and can take place in the following manner:
    - slow transformation processes* (refer to changes in the structures of modules):

$$ST_1[M_i^*(G_2)] \cong ST_0[M_i(G_2)] + \Delta ST[M_i(G_2)]\Delta t, \Delta t \rightarrow T \quad (19)$$

where:

- $ST_0$  – structural parameter of the module  $[M_i(G_2)]$  in the  $[SL_0]$  state of supply chain,
- $ST_1$  – structural parameter of the module  $[M_i^*(G_2)]$  in the  $[SL_1]$  state of supply chain,
- $T$  – supply chain life cycle period
- fast nonlinear processes* (refer to step changes during the cooperation of modules under the influence of changes in their environment):

$$x_1(t) \cong x_0(t) + \Delta x(\Delta t), \Delta t \rightarrow 0 \quad (20)$$

where:

- $x_0$  – parameter of cooperation of modules in the state  $[SL_0]$  of the supply chain,
- $x_1$  – parameter of cooperation of modules in the state  $[SL_1]$  of the supply chain.

### 3.5. Selection of executive modules

The supply chain synthesis model is based on information organized according to the square matrix principles DSM (*Design Structure Matrix*) [12]. Individual cells correspond to the 2-generation modules needed to perform the designed supply chain tasks. Single modules are analysed as components of particular chain links in which specific activities will be performed during the delivery. If the module is not needed for these steps, its value is zero. Only those modules necessary for the performance of appropriate activities in the implementation of a specific procurement task are activated, and their interfaces, as part of the planned activity, are in interaction with at least one other module (Table 2).

In the DSM matrix, the executive module is treated as a component of the supply chain structure. Its exclusion from the structure can be quickly replaced with another module with the same or better functional parameters than the previous version's modules. The module selection procedure is carried out in the following order:

**Step 1: Module's suitability analysis** based on an ordered square matrix; the decision to include new modules in the chain structure is made to meet the requirements of their efficiency, resistance and compatibility. Both basic (obligatory) and supplementary modules can be used, each of which should be appropriately selected to perform specific functions;

**Step 2: Assess the number of modules selected.** Only as many modules as needed for the transport and logistics task should be chosen;

**Step 3: Shaping the sequence of the selected modules.** Laying the structure of supply chains should be carried out, considering the possibility of quick modernization consisting of the efficient replacement of passive modules.

After finalizing the shaping of the sequence of modules, the chain structure should be arranged into one, two, or three module complexes (links). The interactions between links occur according to the logic of unconditional realization of the transport task.

Unplanned changes to the modes of executive processes (rapid changes) lead to bottlenecks and an increased risk of losing the chain's integrity as a whole. Failure to take this into account in the traditional approach causes neglect of the meticulous selection of interfaces and reduces the possibility of using the resistance of individual modules. As an effective tool to meet this requirement, it is proposed to use the "module + interface" combination in the synthesis process, arranged in the ISM (Interface Structure Matrix) presented in Table 3.

Table 2. Ordered matrix of 1st generation modules

Modules	Ordered set of modules									Examination of the supply chain link
	Module $M_1(G_1)$	Module $M_2(G_1)$	Module $M_3(G_1)$	Module $M_4(G_1)$	Module $M_5(G_1)$	Module $M_6(G_1)$	Module $M_7(G_1)$	Module $M_8(G_1)$	Module $M_9(G_1)$	
Module $M_1(G_1)$	1	0	1	x	x	x	x	x	x	Supply module cells
Module $M_2(G_1)$	0	1	1	x	x	x	x	x	x	
Module $M_3(G_1)$	1	1	1	x	x	x	x	x	x	
Module $M_4(G_1)$	x	x	x	1	1	1	x	x	x	Technology module cells
Module $M_5(G_1)$	x	x	x	1	1	0	x	x	x	
Module $M_6(G_1)$	x	x	x	1	1	1	x	x	x	
Module $M_7(G_1)$	x	x	x	x	x	x	1	0	1	Distribution module cells
Module $M_8(G_1)$	x	x	x	x	x	x	1	1	0	
Module $M_9(G_1)$	x	x	x	x	x	x	0	1	1	

Source: own work based on [18]

Table 3. Ordered matrix of inter-module interfaces

Moved goods	Inter-module interfaces									Types of activity
	Module $M_1(G_1)$	Module $M_2(G_1)$	Module $M_3(G_1)$	Module $M_4(G_1)$	Module $M_5(G_1)$	Module $M_6(G_1)$	Module $M_7(G_1)$	Module $M_8(G_1)$	Module $M_9(G_1)$	
Materials, car parts	IWY	IWE	0	x	x	x	x	x	x	Negotiations, purchase, delivery
	0	0	0	x	x	x	x	x	x	
	IWY	IWE	0	x	x	x	x	x	x	
Stocks of auto parts, new cars	x	x	x	IWE	IWY	0	x	x	x	Sorting, storage and picking
	x	x	x	IWE	IWY	0	x	x	x	
	x	x	x	x	x	x	x	IWE	IWY	
New cars	x	x	x	x	x	x	0	IWE	0	Planning, packing, delivery
	x	x	x	x	x	x	0	IWE	0	
	x	x	x	x	x	x	0	IWE	0	

Source: own work based on [18]

- To select the appropriate link, the following approaches are used:
- in the case of similar efficiency and resistance to threats of the analysed interfaces - the selection is made on a discretionary basis;
  - in the case of using the assumption of the need for frequent changes of executive modules - an interface with a high degree of universality is selected, which will not require replacement in the case of replacing the executive modules with new ones;
  - in the case of a high probability of the manifestation of threats - a selection is made by searching for an interface capable of eliminating negative influences from previous interfaces.

#### 4. Case study for the synthesis model taking into account weak synergy effects

##### 4.1. Selection of executive modules

In line with market practice, there are two possible approaches to transforming the structures of supply chains:

1. Division of the functions of the withdrawn module between the remaining modules; in this case, there is a depletion of the Lean Supply Chain, justified not by the pursuit of increasing resilience but by the intention to reduce costs,
2. Without dividing the functions of the withdrawn module between the others and selecting modules that would create conditions for the synergy effects, radically increasing the chain's resistance.

The above means that the synthesis process must be based on selecting modules and using inter-module interfaces, which maximize the probability of positive synergy effects, thus increasing the chain's resistance to adverse events. Therefore, the modelling of synergy effects can be used to measure the effectiveness of cooperation of the supply chain participants.

Accurately selected interfaces ensure the horizontal and vertical fusion of a supply chain designed on the principle of modularity of its components. Such a merger in terms of synchronization has three possible consequences for the bidding companies.

The first one is the possibility of achieving the market position strengthening effect, which is the subject of several studies [11, 19, 47]. On the other hand, the second is the possibility of achieving the multiplier effect, increasing the resistance to adverse events of the connected modules. The multiplier effect is the result of the correct selection of modules, the combination of which in the supply chain generates a synergy of resistance of individual modules interacting within the chain, which can be written:

$$\sum OD_s = k_W (OD_1 + OD_2 + \dots + OD_n) \quad (21)$$

$k_W > 1.0$  –measure of the effectiveness of combining modules (positive synergy effect),

$k_W = 1.0$  – measure of the effectiveness of combining modules (the synergy effect does not arise - the combination of modules is aggregated),

$k_W < 1.0$  – measure of the effectiveness of combining modules (negative synergy effect - asynergy).

The third effect is the possibility of achieving a multiplier effect of lowering overhead costs  $KO$  :

$$\sum KO_s = k_Z (KO_1 + KO_2 + \dots + KO_n) \quad [22]$$

$k_Z > 1.0$  – measure of the effectiveness of combining modules (negative synergy effect - asynergy);

$k_Z = 1.0$  – measure of the effectiveness of combining modules (the synergy effect does not arise - the combination of modules is aggregated);

$k_Z < 1.0$  – measure of the effectiveness of combining modules (positive synergy effect).

##### 4.2. Synergy effects during the cooperation of executive modules

It is assumed that the supply chain structure is in a stable state  $[SL_0]$  and consists of active and passive modules. At some point, under the influence of events, the regular functioning of the chain becomes unstable, and the structure changes to the state  $[SL'_0]$ . Wherein:

1. The  $[SL_{n+1}]$  state was considered at the design stage (all modules are resistant).
2. The state  $[SL_{n+1}]$  was not considered at the design stage and requires the transformation of the chain structure by replacing the passive module with an innovative module.

In case of a decision to replace modules, the structure of the supply chain is transformed into its new state  $[SL_{n+2}]$ , creating conditions for the synergy effects that are:

- short-term (*weak effects*) lasting in the period of inter-module cooperation, in the conditions of a stable structure of the supply chain,

Table 4. Dimensions of the synergy effects during the cooperation of executive modules

Dimensions of the manifestation of effects		Types of synergy effects
1	Effects in the demand dimension	<ul style="list-style-type: none"> <li>• positive, increasing efficiency and resistance to threats;</li> <li>• negative; reducing as efficiency as resistance to threats;</li> </ul>
2	Effects in the supply dimension	<ul style="list-style-type: none"> <li>• possibility to participate in more deliveries;</li> <li>• possibility to access new reliable information;</li> <li>• possibility of access to new technologies;</li> </ul>
3	Effects in the operational dimension	<ul style="list-style-type: none"> <li>• possibility to use partners' resources temporarily;</li> <li>• team resistance to possible threats;</li> <li>• positive image on the demand market</li> </ul>
4	Effects in the structural dimension	<ul style="list-style-type: none"> <li>• binary (as a result of the union of two partners);</li> <li>• general (as a result of joining all partners).</li> </ul>
5	Effects in the time dimension	<ul style="list-style-type: none"> <li>• slow, long-term</li> <li>• quick, short-term</li> </ul>
6	Effects in the economic dimension	<ul style="list-style-type: none"> <li>• possibility to reduce accumulated stocks;</li> <li>• joint responsibility for possible risks of financial losses;</li> <li>• diversification of delivery costs to a larger number of subcontractors.</li> </ul>

Table 5. Input information for comparative analysis of synergy effects

Cooperation mode	Graphical representation	Calculation formula
1. Parallel mode		$1) P(t) = 1 - \prod \{1 - p_z[M_z(t)]\}$ $2) P^*(t) = 1 - \prod \{1 - p_z^*[M_z(t)]\}$ $3) \Delta ES = \frac{P^*(t) - P(t)}{P^*(t)}$
2. Serial mode		$1) P(t) = p_i[M_i(t)] \times p_k[M_k(t)]$ $2) P^*(t) = p_i[M_i^*(t)] \times p_k[M_k(t)]$ $3) \Delta ES = \frac{P^*(t) - P(t)}{P^*(t)}$

- long-term (*strong effects*) generating changes in the structures of cooperating modules, in the conditions of modernization changes in the supply chain structure.

It is proposed to apply three steps to the study of weak synergy effects:

**Stage 1.** Integrated two- or three-module complexes are created from the 2nd generation modules. For example, the complex  $[M_i(G_2)] \cup [M_k(G_2)]$  combines the module  $[M_i(G_2)]$  presenting the transport company and the module  $[M_k(G_2)]$  presenting the Regional Logistics Center. The research at this stage concerns methods of collecting and analyzing information and techniques for detecting missing information.

**Stage 2.** Single complexes are combined in an integrated structure of the supply chain. In this case, the research concerns development of a rational chain structure (continuous, efficient and sufficient) and the impact of events on the ability of the supply chain to perform the task. The power of the chain depends on the performance and resilience of each module  $[M_i]$ , both properties being independent.

**Stage 3.** After completing the task, the chain structure is decomposed. By examining the effects during intermodal cooperation and when the reversibility condition is met (according to which modules  $[M_i(G_2)]$  and  $[M_k(G_2)]$  are disconnected), it maintains the original internal structure.

The highest capacity of the supply chain to perform task occurs when events  $ZD_1$  and  $ZD_2$  occur during the cooperation of modules  $[M_1(G_2)]$  and  $[M_2(G_2)]$ . Such synergy effects can occur in various dimensions (Table 4).

The emergence of synergy effects is three-dimensional and consists of indicating the value of such effects, assessing the pace of their formation, and assessing the impact on the transport and logistics capacity of the entire chain (positive or negative).

#### 4.3. Example of a comparative analysis of synergy effects

A comparative analysis of the synergy effects for the cooperation of two modules in parallel and serial mode will be performed (Table 5). It is assumed that within the analysed complex two modules were connected -  $[M_i(G_2)]$  and  $[M_k(G_2)]$ . During the transport and logistics activities, the module  $[M_i(G_2)]$  lost its resistance to threats

to a large extent. A decision was made to replace this module with the innovative  $[M_i^*(G_2)]$ .

The possible effect of such an exchange will be assessed. The following parameters were used as part of the analysis:

- $P(t)$  – probability of resilience of an unreliable complex of modules  $[M_i(G_2)]$  and  $[M_k(G_2)]$ ;
- $P^*(t)$  – probability of resilience of modernized complex of modules  $[M_i^*(G_2)]$  i  $[M_k(G_2)]$ ;
- $p_k(t)$  – probability of resilience of the active module  $[M_k(G_2)]$ ;
- $p_i(t)$  – probability of resilience of a passive module  $[M_i(G_2)]$ ;
- $p_i^*(t)$  – probability of resilience of a innovative module  $[M_i^*(G_2)]$ ;
- $\Delta ES$  – synergy effect from cooperation of modules  $[M_i^*(G_2)]$  and  $[M_k(G_2)]$ .

To conduct a comparative analysis, the following assumptions are made:

1. The service life of  $[M_i(G_2)]$  and  $[M_k(G_2)]$  modules within a single complex are 5 years.
2. The loss of the complex's resilience to threats occurs when this property is lost by at least one module connected in series with the second module.
3. The loss of resilience of each module occurs irrespective of the state of the other module.
4. The dynamics of the loss of resilience to threats by both modules is linear.
5. The module  $[M_i(G_2)]$  has an accelerated dynamics of the loss of resilience in relation to  $[M_k(G_2)]$ .
6. The innovative module  $[M_i^*(G_2)]$  has the resilience  $P = 0,99$ .
7. Inter-module interfaces are considered to be absolutely reliable.

The results of the simulation are presented in Table 6. The comparative analysis shows that:

Table 6. Test results for weak synergy effects

Parameters	Passive period before module replacement				
	1 year	2 years	3 years	4 years	5 years
$p_i(t) / p_i^*(t)$ parallel mode	0,952/0,990	0,893/0,990	0,851/0,990	0,782/0,990	0,721/0,990
$p_k(t)$ parallel mode	0,981	0,963	0,942	0,926	0,901
$P(t) / P^*(t)$ parallel mode	0,9991	0,9962	0,9914	0,9840	0,974
	0,9981	0,9963	0,9942	0,9926	0,9912
$\Delta ES$ parallel mode of cooperation	<b>Synergy effect in a complex with the parallel mode of modules cooperation</b>				
	-0,011 %	0,0%	0,28%	0,86%	1,73%
$p_i(t) / p_i^*(t)$ serial cooperation mode	0,952/0,990	0,893/0,990	0,751/0,990	0,652/0,990	0,550/0,990
$p_k(t)$ serial cooperation mode	0,981	0,963	0,942	0,926	0,901
$P(t) / P^*(t)$ of serial modules	0,935	0,821	0,707	0,604	0,496
	0,971	0,953	0,934	0,907	0,892
$\Delta ES$ serial cooperation mode	<b>Synergy effect in a complex with the serial mode of modules cooperation</b>				
	3,71 %	4,56%	7,07%	6,05%	4,96%

- replacement of passive modules with active ones is advisable in the case of complexes with a serial mode of their cooperation. The values of these effects range from 3,5-7,1%;
- the most effective is a replacement in the 2-4 years of operation of the supply chain,
- it is less effective to replace passive modules with active ones in the case of complexes with a parallel mode of cooperation. However, such a replacement for a 1-year operation may be contraindicated, as it may cause adverse synergy effects,
- after the second year of operation, synergy effects with 0,5% positive dynamics can be observed.

## 5. Conclusions

Transport and logistics companies are rational in their economic activities by engaging only in projects maximizing their financial liquidity. The disadvantages of the traditional approach are:

- no desire to integrate with other companies on a “win-win” basis,
- too much space for possible solutions, lack of transparency and stability of knowledge about opportunities to strengthen the market position.

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