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RISK-ORIENTED SIMULATION OF THE LONG LOGISTICS SUPPLY CHAINS IN DEVELOPING ENTERPRISES

The paper defines and solves the urgent problem of research of long logistics supply chains in developing enterprises. Due to the distribution of the production system as well as to the presence of a large number of remote suppliers of materials, raw materials and components supply plans are threatened. Supply disruptions in their turn may affect the plans of the main production resulting in possible fines, economic losses, and disruptions in supply of manufactured articles to the markets of high-tech and science-intensive products. To study threats and vulnerabilities in supply logistics the risk-oriented approach that considers potential threats using past statistics and expert assessments has been proposed. The objective of the paper is to develop a risk-oriented method to study the existing threats and assess their impact on the vulnerabilities of the logistics chains of the distributed production system. Due to the complexity of the problematic logistics task, the study is conducted in three different stages: development of the method to simulate the risks in long supply chains; identification of possible bottlenecks in the transport system of supply logistics; threat simulation and vulnerability analysis in supply logistics. To model the risks, an agent model is used, in which the accumulation of risks is carried out by passing orders in the transport system. To simulate bottlenecks, a simulation event model is used, in which large queues that occur in the transport system are analyzed. A stochastic simulation model is used to model threats and vulnerabilities. The new scientific results are risk-oriented method of long logistics supply chains simulation; simulation of supply logistics threats and vulnerabilities. Mathematical methods used: risk theory; simulation event modeling; agent modeling; queuing theory. The proposed approach as a set of developed simulation models should be used to plan the supply of developing production.

Keywords: *logistic risks; supply of distributed production; threats and vulnerabilities in transport logistics; simulation modeling; agent modeling.*

Introduction

The globalization of the economy has led to the need to organize the production process associated with a large number of suppliers for creation and production of high-tech and science-intensive products (aerospace, shipbuilding, etc.) [1]. Currently there are long and sometimes confusing logistics chains that must ensure the continuity of the production process in a distributed production cycle. At the same time there are risks of supply of various nature and forms (border crossing, climatic factors, terrorist threats, disturbance of routes, etc.) [2, 3]. Typical example of the risks of long supply chains is the disrupted passage of ships in the Suez Canal because of the "Ever Given" container ship, which ran aground in the canal lock on March 23, 2021, and traffic disruptions in the Bosporus on May 29, 2021 due to an oil tanker stuck at the high tide. These critical situations have led to disruptions in the supply of electronic and automotive components, as well as energy for leading automotive companies, which led to decline of output and economic losses. Therefore, the current topic of the proposed publication is setting and solving the problem of minimizing the risks associated with long supply chains in the formation of logistics services for the portfolio of new production orders in development [4, 5].

1. Problem statement

Due to the complexity of the research task, the solution requires the following steps:

1. Development of a method for modeling risks in long supply chains.
2. Identification of possible bottlenecks in supply logistics.
3. Threat simulation and vulnerability analysis in supply logistics.

2. Risk simulation in long supply chains

Simulation of supply risks is associated with the analysis of traffic routes, cargo and accumulation of risks in the passage of sections and nodes of heterogeneous transport system (TS) [6]. It is necessary to take into account the risks of possible transshipment of goods from one mode of transport to another (for example, sea to rail). The proposed method of simulation of possible supply routes is based on the use of simulation event modeling, in which the main factors are the risks of cargo passing through route sections and transport nodes of heterogeneous TS taking into account transshipments.

The main events in the simulation model are: the "arrival" event to the route section (between adjacent transport nodes); "departure" event from the route section; "arrival" event to the transport node; "departure" event from the transport node. Each cargo in the simulation will be presented as an order that moves from the supplier to the production system. The heterogeneous transport network is presented in the form of a marked graph, where orders of different type cans be marked with different colors. The graph is not oriented, which allows movement of the order in any direction, from the node under consideration. The concept of "weight" is introduced, both for the route section and for the transport node. The risk of passing through the i^{th} route section (r_i), and through the j^{th} transport node (r_j) is used as "weight". In the process of movement of orders (cargo), the risks are accumulated in the form of additive representation:

$$R = \sum_{i=1}^{m} r_i + \sum_{j=1}^{n} r_j ,$$

where m is the number of route sections passed;

n is the number of transport nodes passed.

The search for the route that corresponds to the minimum accumulated risk R is carried out using the developed simulation algorithm:

1. Generate an order (cargo) from the j^{th} node.

2. Move the order from the j^{th} node on the i^{th} route section with the value of risk r_i.

3. When the order enters the next j+1 transport node, it marks it with the i^{th} mark, which means that the order got to this node first. In this case, the accumulation of risk R associated with the passage of the order of the previous TS sections and components.

4. Copies (clones) of the order are generated in all directions (sections) from this j^{th} node in a heterogeneous TS.

5. If the order or its clone in its movement moves to the transport node previously marked by another order, its movement is halted (the order is canceled), because it means that the previous order (clone) has already passed this node with less risk.

6. The movement of the order is halted in the event that the order has entered the TS dead end node.

7. As soon as the order has reached the production node, the order simulation is stopped and the algorithm is halted. This results in the route of cargo movement from the supplier to production with a minimum risk value:

$$\min R; R = \sum_{i=1}^{m} r_i + \sum_{j=1}^{n} r_j .$$

8. The route trajectory is formed with the markers in TS graph vertices marked by the order.

The implementation of the developed method was carried out using the agent model of simulation event modeling on the JADE platform [7]. The set of agents consists of the following:

1 – agent of order generator (RG);

2 – agent of arrival order to the i^{th} transport route section (TRS);

3 – agent of order departure from the i^{th} transport route section (TRS);

4 – agent of arrival order to the j^{th} transport node (TN);

5 – agent of arrival order from the j^{th} transport node (TN);

6 – agent of risk accumulation R;

7 – agent for traffic route generation (TR);

8 – monitoring agent (event management, time);

9 – agent for forming the structure of a heterogeneous TS.

Fig. 1 shows the structure of the agent model for the study of risks in logistics supply chains (LSC).

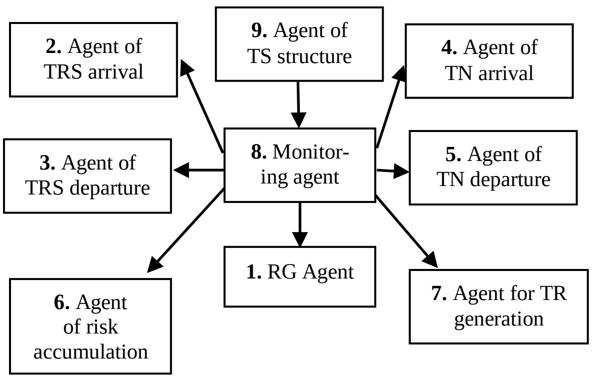

Fig. 1. The agent model structure for risk study in logistics supply chains

3. Identification of possible bottlenecks in supply logistics

Analysis of possible bottlenecks in long supply chains requires study of the dynamic process of cargo movement with different intensities of orders to a heterogeneous transport network [8].

This requires determination of possible values (range) of order intensities L, which arrive to a heterogeneous TS. This uses the existing statistics of intensities of cargo arriving to TS $L_1 \le L \le L_2$, where L_1 is the minimum value of intensity L, and L_2 is the maximum value of L. Changing the intensity of cargo supply can lead to changes in TS capacity and queues for orders at TS route sections and transport nodes. This paper con-

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siders the route sections and nodes with long queues of orders as TS bottlenecks. Simulation modeling in agent execution is used to simulate queues in the delivery dynamics. The list of used agents in the simulation model consists of the following:

1 – agent of order generator;

2 – device agent. This agent is used to describe route sections and TS nodes where time delays associated with the passage of orders occur. If parallel service of orders is possible, the device is presented in the form of a multi-channel service device;

3 – queue agent. These agents are used to form order queues in case of occupancy of route sections and TS nodes servicing current orders;

4 – agent of description of a heterogeneous transport network (devices and connections between them are specified);

5 – agent of statistics collection (queue length: minimum, average, maximum);

6 – agent of TS capacity (minimum, average, maximum);

7 – monitoring agent. This agent monitors system time, plans events, manages the flow of orders throughout route sections and TS nodes.

Fig. 2 shows a block diagram of an agent model to study bottlenecks in supply chains.

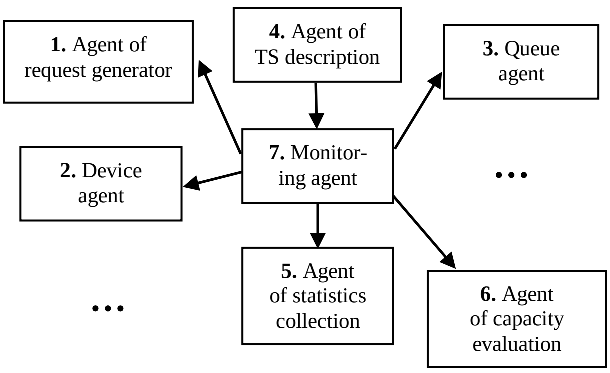

Fig. 2. Block diagram of the agent model of research of bottlenecks in logistics supply chains

Research on the occurrence of queues at route sections and at TS nodes requires the conduct of experiments using the built agent model with changing the values of order intensities arriving to TS upon delivery.

In order to reduce the study time, it is possible to conduct experiments for the lower limit of the intensity range, the upper and the average value.

The obtained values of queue lengths at sections and TS nodes must be presented in the form of a ranked series P_1, P_2,…, P_S, where in the first place (P_1) is the section or TS node with the longest queue (potentially bottleneck), and at the end (P_S) – with the smallest queue.

The bottlenecks found may be the subject of further research aimed at eliminating them.

4. Threat simulation and vulnerability analysis in supply logistics

In long supply chains may occur vulnerabilities, which under the influence of possible threats lead to failures and emergencies on route sections and heterogeneous TS nodes [9].

Therefore, it is important to analyze vulnerabilities and assess the impact of threats that cause vulnerabilities, which can lead to losses, supply disruptions, disruption of production plans, additional financial costs, as well as possible fatalities.

Thus, in order to assess the emergence of threats and vulnerabilities in long supply chains, it is necessary to constantly monitor and collect statistics, involve experts who assess the risks of their occurrence, as well as possible losses from their manifestation.

This paper studies threats and vulnerabilities in several stages.

At the first stage, with the help of experts and the use of accumulated statistics, a set of potentially dangerous places (vulnerabilities) in a heterogeneous TS is formed.

Then, using a score scale (for example, 0÷10), the level of vulnerability associated with the threat is assessed.

The obtained values are initial for the configuration of vulnerability generators in the simulation model, which occur when the corresponding threats appear.

In order to link threats and relevant vulnerabilities, a table (Table 1) of possible threats and their correspondence to vulnerabilities is built, where r_{ji} represents the risk of vulnerability in the event of a threat.

Empty spaces in Table 1 mean no impact of threats on vulnerabilities.

Table 1

Risks in the event of threats and vulnerabilities

Threat No.	**Vulnerability**				
	Z_1	Z_2	Z_3	**…**	Z_W
Y_1		r_{12}			r_{1W}
Y_2	r_{21}		r_{23}		
…					
Y_M		r_{M2}			r_{MW}

At the next stage, a simulation event model is built to study the disruption of supply plans in a heterogeneous TS due to the emergence of threats and possible manifestation of vulnerabilities. The simulation is performed repeatedly with the subsequent analysis and averaging of the simulation results. At the beginning of each simulation cycle, the presence of threats is determined using a threat generator. Critical places are formed in heterogeneous TS (route sections and TS nodes) taking into account the manifestation of vulnerabilities. With the help of supply order generators (see the previous stages of the study) orders are formed, which move in a heterogeneous TS to production. Upon arriving the current route section or TS transport hub, the presence of vulnerabilities is determined using risk assessments (Table 1). In case of detection of a vulnerability, a time delay occurs associated with its elimination or neutralization of possible damage from the vulnerability. If the vulnerability leads to the failure of the route section or TS node, the simulation is halted to find possible ways to bypass the TS emergency node or route section using the reproduction of orders (clones). In the absence of a bypass for the movement of orders in a heterogeneous TS, the algorithm stops, which indicates a possible disruption of supply. To investigate supply plan disruptions related to threats and vulnerabilities, simulations are performed multiple times to obtain the most accurate evaluation.

The simulation model is presented in the form of agents. The structure of the agent model consists of the following:

1 – agent for structure of heterogeneous TS;

2 – agent for route sections (RS) with possible vulnerabilities;

3 – agent for transport node (TN) with possible vulnerabilities;

4 – risk generator agent (RG) for r_{ji} manifestations of vulnerabilities from relevant threats;

5 – agent for generation of time delays (TD) associated with the occurrence of damage from the vulnerabilities;

6 – agent for generation of order copies (clones) for bypassing emergency route sections or transport nodes;

7 – statistics agent. This agent is used to collect statistics on the results of multiple simulations to assess violations of the supply plan;

8 – TD agent when passing orders throughout TS nodes;

9 – TD agent when passing orders throughout route sections of heterogeneous TS;

10 – monitoring agent. This agent monitors system time, plans and implements a list of future events.

Fig. 3 shows the structure of the agent simulation model for the study of threats and vulnerabilities in heterogeneous TS.

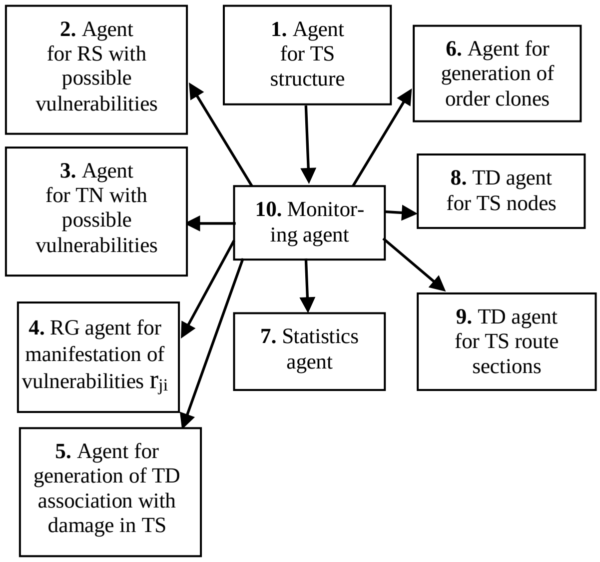

Fig. 3. Structure of the agent model for the study of threats and vulnerabilities in the transport system

5. Example of supply risk research

The paper further considers an illustrated example of using the proposed method to find a route in TS with minimal risk in the supply logistics (Fig. 4).

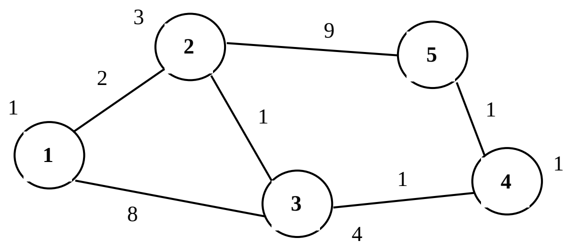

Fig. 4. Example of finding a route with minimal risk

In Fig. 4, the numbers are placed at the graph vertices, and risks are placed above the edges and vertices.

Assume that vertex 1 of the transport system graph is related to the component supplier whereas vertex 5 of the transport system is connected to the production. For each vertex of the graph, as well as the edges connecting the vertices (route sections), the risk assessments associated with the passage of orders are known. The orders depart from the vertex 1 and in the form of clones enter the edges 2 and 3. The values of the accumulated risk in the edge 2 and edge 3 equal 6 (R=6) and 13 (R = 13) respectively. The clones that arrive to the vortices 2 and 3 mark them with and begin to reproduce. From vertex 2, the orders move to vertices 3 and 5, and from vertex 3 to vertices 2 and 4. The accumulated risk in vertex 3 for the order that arrived from vertex 2

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equals 11 (R=11). For an order that arrived from vertex 1, the risk equals 13 (R=13). For an order that arrived from vertex 2 and reached vertex 3, the risk is less (R=11). This means that an order that arrived from the vertex 1 and reached the vertex 3 will be rejected due to the greatest risk (R=13). Further, the paper considers the movement of orders from vertex 2 to vertex 5 and from vertex 3 to vertex 4, and then to vertex 5. The final vertex 5 (production) receives an order for route 1,2,5 with risk (R=15) and route 1,2,3,4,5 with risk (R=14). This demonstrates that the first order is received on route 1,2,3,4,5, which marks the vertex 5. The order on route 1,2,5 is received later due to the highest risk value (R=15) and that is why it will be rejected. The final route with the minimum value of risk (R=14) consists of vertices and edges of the graph and corresponds to the sequence of movement of cargo 1,2,3,4,5 from the supplier to the production.

Conclusions

The publication examines the long supply chains of a developing enterprise. A risk-oriented method of risk simulation in supply logistics to find a route from suppliers to production with minimal risk has been developed. A simulation event model has been developed, which accumulates risks in long supply chains during the movement of cargo in a heterogeneous TS. Queues simulation in the dynamics of cargo movement in a heterogeneous TS helped to identify bottlenecks that lead to disruptions of delivery times, materials, raw materials, components in a distributed TS. A method for threats and vulnerabilities simulation in long supply chains has been developed, and their impact on key targets in a distributed production system when planning new order portfolios has been evaluated.

The proposed approach is advised in the formation of targets and the generation of routes, materials, raw materials and components of developing production.

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РИЗИКО-ОРІЄНТОВАНЕ МОДЕЛЮВАННЯ ДОВГИХ ЛОГІСТИЧНИХ ЛАНЦЮЖКІВ ПОСТАЧАННЯ В ПІДПРИЄМСТВАХ, ЩО РОЗВИВАЮТЬСЯ

О. Е. Федорович, Ю. Л. Прончаков

Ставиться та вирішується актуальна задача дослідження довгих логістичних ланцюжків постачання в підприємствах, що розвиваються. З-за розподіленості виробничої системи та наявності великої кількості віддалених постачальників матеріалів, сировини та комплектуючих, виникають загрози зривів планів постачання, що відображується на планах основного виробництва у вигляді їх порушень, які призводять до можливих штрафів, економічних втрат та порушенню постачання виробленої продукції на ринки високотехнологічних та наукоємних виробів. Для дослідження загроз та вразливостей у логістиці постачання запропоновано ризико-орієнтований підхід, який враховує можливі загрози з допомогою минулої статистики і оцінок експертів. Метою роботи є розробка ризико-орієнтованого методу для дослідження існуючих загроз та оцінка їх впливів на вразливості логістичних ланцюжків розподіленої виробничої системи. З-за складності проблемної логістичної задачі, дослідження проводиться у три етапи: розробка методу моделювання ризиків в довгих логістичних ланцюжках постачання; визначення можливих вузьких місць в транспортній системі логістики постачання; моделювання загроз та аналіз вразливостей в логістиці постачання. Для моделювання ризиків використовується агентна модель, в якій здійснюється накопичення ризиків шляхом проходження заявок в транспортній системі. Для моделювання вузьких місць використовується імітаційна подійна модель, в якій аналізуються великі черги, які виникають в транспортній системі. Для моделювання загроз та вразливостей використовується стохастична імітаційна модель. Новими науковими результатами є: ризико-орієнтований метод імітаційного моделювання довгих логістичних ланцюжків постачання; моделювання загроз та вразливостей логістики постачання. Використані математичні методи: теорія ризиків; імітаційне подійне моделювання; агентне моделювання; теорія масового обслуговування. Запропонований підхід у вигляді комплексу розроблених імітаційних моделей доцільно використовувати при формування планів постачання виробництва, що розвивається.

Ключові слова: логістичні ризики; постачання розподіленого виробництва; загрози і вразливості у транспортній логістиці; імітаційне моделювання; агентне моделювання.

РИСК-ОРИЕНТИРОВАННОЕ МОДЕЛИРОВАНИЕ ДЛИННЫХ ЛОГИСТИЧЕСКИХ ЦЕПОЧЕК ПОСТАВОК В РАЗВИВАЮЩИХСЯ ПРЕДПРИЯТИЯХ

О. Е. Федорович, Ю. Л. Прончаков

Ставится и решается актуальная задача исследования длинных логистических цепочек поставки в развивающихся предприятиях. Из за распределенности производственной системы и наличия большого коли-

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чества отдаленных поставщиков материалов, сырья и комплектующих, возникают угрозы срыва планов снабжения, что отображается на планах основного производства в виде их нарушениях, которые приводят к возможностям штрафов, экономических потерь и нарушений поставки произведенной продукции на рынки высокотехнологичных и наукоемких изделий. Для исследования угроз и уязвимостей в логистике снабжения предложен риск-ориентированный подход, который учитывает возможные угрозы с помощью прошлой статистики и оценок экспертов. Целью работы является разработка риск-ориентированного метода для исследования существующих угроз и оценка их влияния на уязвимости логистических цепочек распределенной производственной системы. Из-за сложности проблемной логистической задачи, исследование проводится в три этапа: разработка метода моделирования рисков в длинных логистических цепочках поставок; определение возможных узких мест в транспортной системе логистики снабжения; моделирование угроз и анализ уязвимостей в логистике поставки. Для моделирования рисков используется агентная модель, в которой осуществляется накопление рисков путем прохождения заявок в транспортной системе. Для моделирования узких мест используется имитационная событийная модель, в которой анализируются большие очереди, возникающие в транспортной системе. Для моделирования угроз и уязвимостей используется стохастическая имитационная модель. Новыми научными результатами являются: риск-ориентированный метод имитационного моделирования длинных логистических цепочек поставок; моделирование угроз и уязвимостей логистики снабжения. Использованы математические методы: теория рисков; имитационное событийное моделирование; агентное моделирование; теория массового обслуживания. Предложенный подход в виде комплекса разработанных имитационных моделей целесообразно использовать при формировании планов снабжения развивающегося производства.

Ключевые слова: логистические риски; поставки распределенного производства; угрозы и уязвимости в транспортной логистике; имитационное моделирование; агентное моделирования.

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