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Ripple effect impact on the resilience of the perishable products supply chains

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1. GENERAL CHARACTERISTICS OF THESIS RESEARCH

Motivation & Research Gap. The number of external factors affecting the resilience of supply chains is growing every year. According to Resilinc research, 97% of global companies experienced significant supply chain disruptions in 2020. This value is up 67% from the 2019 value[1]. The complexity of dealing with disruptions in today's supply chains is related to the logistics network configuration, processes, and product features. It should also be noted that different types of supply chain disruptions have different mechanisms of impact. One example of a complex atypical impact is the aftermath of the COVID-19 pandemic, which demonstrated the dependence of supply chains on external negative factors. In this case, disruptions blocked the supply chains of entire regions at different periods. Just as an epidemic generally spreads in waves, from the first months of exposure to the risk event, there was a significant disproportion in the balance of demand, supply, and available production capacity. The ability to predict the development of the risk factors was also limited. Other known causes of significant supply chain disruptions in the past few years include Hurricane Sandy in 2012 or the tsunami off the coast of Japan in 2011. The increasing complexity of the impact of adverse risk events has led to a reassessment of the components of supply chain resilience.

The supply chain resilience term is transforming as the number of papers on the topic increases. Some researchers have proposed the term "viability" as a separate term[2]. This notion develops the original meaning with a greater focus on the long-term functioning of supply chains and interaction with the "outside" world, taking into account social and environmental factors. This broadening of the scope of the challenges studied favors the application of optimization tools and the creation of digital supply chain twins, as the ability to effectively predict key scenarios of the impact of risk events is critical to assessing the long-term dynamics of the supply chain performance.

One such important negative long-term factor is the high level of write-offs in supply chains. The risks of write-offs are a significant problem even not considering the goal of improving supply

[1] Resilinc. Resilinc 2020 Annual Report. Carpe Diem / Resilinc. – 2020. URL: https://www.resilinc.com/learning-center/white-papers-reports/ (accessed at: 25.04.2022).
[2] Ivanov, D. Viable supply chain model: integrating agility, resilience and sustainability perspectives – lessons from and thinking beyond the COVID-19 pandemic / D. Ivanov // Annals of Operations Research. – 2020. – P. 337–357.

chain resilience; the share of write-offs can exceed 30%[3,4] of the original production of some product groups. Incorrect demand forecasts, lack of supply chain coordination, and limited product shelf life are essential factors affecting write-off levels[5].

One of the components of supply chain dynamics is the process of spreading the negative consequences of a disruption (external or internal), referred to as the “ripple effect”. This effect has a significant impact on supply chain performance at all stages of the impact of a negative event. The ripple effect manifests itself in varying degrees depending on the configuration of the supply chain and the external environment.

The initial propagation of a risk event, as well as the stabilization of the supply chain after recovery, are complex dynamic processes, for the description of which various statistical methods[6], operations research methods[7,8], and simulation are used[9,10].

All three basic simulation paradigms are used in various combinations for supply chain resilience research: system dynamics[11,12], discrete event simulation[13], multi-agent simulation[14,15,16].

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[3] Rodrigues, V.S. Measurement, mitigation and prevention of food waste in supply chains: An online shopping perspective / V.S. Rodrigues, E. Demir, X. Wang // Industrial Marketing Management. – 2021. – Vol. 93. – P. 545–562.

[4] Buzby, J.C. Supermarket loss estimates for fresh fruit, vegetables, meat, poultry, and seafood and their use in the ERS loss-adjusted food availability data / J.C. Buzby, H.F. Wells, B. Axtman, J. Mickey // United States Department of Agriculture, Economic Information Bulletin. – 2009. – Vol. 44. – P. 1–20.

[5] Moraes, C.C. Retail food waste: mapping causes and reduction practices / C.C. Moraes, F.H. Oliveira Costa, C. Roberta Pereira, A.L. da Silva, I. Delai // Journal of Cleaner Production. – 2020. – Vol. 256. – P. 120–124.

[6] Hosseini, S. A new resilience measure for supply networks with the ripple effect considerations: a Bayesian network approach / S. Hosseini, D. Ivanov // Annals of Operations Research. – 2019. – P. 1–27.

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[8] Snyder, L.V. OR/MS models for supply chain disruptions: A review / L.V. Snyder, Z. Atan, P. Peng, Y. Rong, A.J.Schmitt, B. Sinsoysal // IIE Transactions. – 2016. – Vol. 48. – N 2. – P. 89–109.

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[10] Schmitt, A.J. A quantitative analysis of disruption risk in a multi-echelon supply chain / A.J. Schmitt, M. Singh // International Journal of Production Economics. – 2012. – Vol. 139. – P. 22–32.

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[13] Carvalho, H. A supply chain redesign for resilience using simulation / H. Carvalho, A.P. Barroso, V.H. Machado, S. Azevedo, V. Cruz-Machado // Computers and Industrial Engineering. – 2012. – Vol. 62. – P. 329–341.

[14] Ivanov, D. Revealing interfaces of supply chain resilience and sustainability: a simulation study / D. Ivanov // In International Journal of Production Research. – 2018. – Vol. 56. – N 10. – P. 3507–3523.

[15] Singh, S. Impact of COVID-19 on logistics systems and disruptions in food supply chain / S. Singh, R. Kumar, R. Panchal, M.K. Tiwari // International Journal of Production Research. – 2021. – Vol. 59. – N 7. – P. 1993–2008.

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The majority of the articles on the ripple effect have been published since 2014[17,18]. The ripple effect can be characterized as one of the dynamic components of the concept of supply chain resilience, formulated in the works of 2003–2005[19,20,21]. The concept of supply chain resilience draws on similar research in systems theory[22], ecology[23], psychology, and geology performed in the 1940s–1970s[24]. In general, resilience can be characterized as the ability after a significant negative impact (a risk event or a disruption) to return to a state comparable in effectiveness to the state before the adverse event occurred.

Supply chain management has the following options for handling a negative risk event: to prepare additional capacity in advance (proactive strategy), use alternative sources of supply (reactive strategy), or take no countermeasures. Simulation modeling can capture both reactive and proactive strategies.

According to a study[25] on supply chain resilience assessment published before 2017, simulation-based approaches are among the best for real-time system analysis. This method is also effective for problems with many parameters affecting supply chain recovery after a disruption. The majority of the ripple effect studies balance the size of the network being studied and the granularity of the processes. A review of publications from 2017–2019[26] highlights no single definition of the ripple effect in the literature, but a consensus on the term has emerged. There is also a trend toward the use of artificial intelligence and machine learning in this area.

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[17] Ivanov, D. Optimal distribution (re)planning in a centralized multistage supply network under conditions of the ripple effect and structure dynamics / D. Ivanov, A. Pavlov, B. Sokolov // European Journal of Operational Research. – 2014. – Vol. 237. – P. 758–770.

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[22] Zhao, K. Modelling supply chain adaptation for disruptions: An empirically grounded complex adaptive systems approach / K. Zhao, Z. Zuo, J.V. Blackhurst // Journal of Operations Management. – 2019. – Vol. 65. – N 2. – P. 190–212.

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Three main components of supply chain resilience[27], the “lines of defense”, can be distinguished: absorptive capacity, adaptive capacity, and restorative capacity. This classification can be used to group existing research on this topic. Consideration of all three types of capacity requires the formulation of a complex optimization target function. Thus, dynamic modeling is a suitable tool for solving this problem.

The propagation of the consequences of a disruptive event can cause implicit interaction of the supply chain links. This interaction is difficult to predict and model. The ripple effect in supply chains can be considered in the context of a supply chain resilience framework consisting of three layers: network structure, process planning (proactive measures), operational control (reactive measures)[28]. The forward propagation of the consequences of supply chain disruption has been investigated to the greatest extent and is presented in many papers. At the same time, in some cases, the disruption of an intermediate echelon of the supply chain can cause instability of the entire supply chain.

The direction of the “ripples” of the impact of an adverse event in the supply chain can also be reversed (towards the suppliers of raw materials) [29]. The specifics of the spread of this effect depend on the dynamics and configuration of the logistics network and can manifest themselves differently at different stages of the disruption. This “closed-loop” approach can be implemented in several ways but almost always requires the construction of complex optimization models or additional splitting of the problem into components. For example, a linear programming model can be decomposed into two parts: the main model and the network recovery model[30]. The optimization of parameters is performed separately for each submodel.

The following trend can be identified: the more complex the dynamics of the system or the more specific the influence of individual parameters, the more often simulation is applied. This statement is also true for situations where the dimensionality of the problem increases. Supply chain resilience is closely related to the “Efficiency/Redundancy” relationship by analogy with the

[27] Hosseini, S. Review of quantitative methods for supply chain resilience analysis / S. Hosseini, D. Ivanov, A. Dolgui // Transportation Research Part E: Logistics and Transportation Review. – 2019. – Vol. 125. – P. 285–307.
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[30] Goldbeck, N. Optimal supply chain resilience with consideration of failure propagation and repair logistics / N. Goldbeck, P. Angeloudis, W. Ochieng // Transportation Research Part E: Logistics and Transportation Review. – 2020. – Vol. 133. – N 101830. – P. 1–20.

"Cost/Service Level" relationship[31,32]. In addition, increasing inventory levels and redistributing inventory within the network are important components of supply chain resilience. Limited product shelf life and write-off risks increase the complexity of inventory planning algorithms since the strategy of preventively increasing inventory levels can be used in a limited way only.

Important features of supply chain management for products with a limited shelf life include the risks of product write-offs and customer segmentation by remaining shelf life requirements[33,34]. Furthermore, when a logistics network disruption happens, these characteristics significantly impact the supply chain performance[35]. Therefore, supply planning algorithms for products with a limited shelf life must take into account the physical absence of products and the requirements and characteristics of the customers who purchase these products[36]. Thus, it is possible to distinguish between the concepts of nominal shelf life and real shelf life, defining a period during which it is possible to sell the products.

The basic algorithms for planning the supply of products with a limited shelf life were formulated from 1972–1981[37]. Many works have been devoted to special variants of the problem formulation using operations research[38,39]. When the shelf life of products is limited, some of the measures to reduce the negative impact of supply chain disruption are much less effective, e.g., additional buffer product stock leads to higher risks of product write-offs. For this reason, the analysis of supply chain dynamics of this type is a promising area of study.

Optimization models considering the shelf life constraints can be an integral part of advanced planning & scheduling (APS) systems[40]. The main methods used to optimize the supply planning

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[31] Carvalho, H. A supply chain redesign for resilience using simulation / H. Carvalho, A.P. Barroso, V.H. Machado, S. Azevedo, V. Cruz-Machado // Computers and Industrial Engineering. – 2012. – Vol. 62. – P. 329–341.
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of products with a limited shelf life: analytical methods, operations research, simulation, and empirical studies[41].

Priority scheduling rules (issuing policies in inventory management) analysis is a separate research stream[42,43]. In most cases, FIFO (First In – First Out) shows better performance in terms of the total cost[44].

Designing a logistics network for products with moderate write-off risks implies a large number of possible configurations. The shelf life of products can be long enough that the product stock is represented by a multidimensional vector (dimensions: number of units in the stock lot, production period), but the risks of write-offs are relatively low. But in this configuration, changes in network structure or processes caused by a supply chain disruption can lead to a dramatic increase in write-offs levels.

In particular, the LEFO (Last Expired – First Out) policy is also applied in practice and is in many ways similar to LIFO (Last In – First Out). This policy has a limited effect on the service level but is directly related to the write-off costs. Using this inventory depletion policy often causes a higher level of write-offs. Therefore, increasing the inventory does not result in improved system performance. In addition, product shelf life constraints cause backlogs to be virtually inapplicable, even though they are appropriate for products without shelf life constraints. This type of product shortage has been studied in detail in many supply chain resilience studies. Compensation of this postponed demand is one factor that leads to the reduction of the ripple effect during the recovery and stabilization stages of the supply chain.

The combination of limited shelf life and supply chain disruption makes applying sophisticated analytical and modeling techniques essential. In particular, simulation describes supply chain dynamics during disruptions and inventory management models for perishable products. Other commonly used methods are Bayesian networks, mixed-integer optimization models. In addition, simulation modeling has the advantage of describing a process at a given level of detail. Thus, this method allows a more accurate description of the stages of the supply chain response to adverse effects.

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[41] Haijema, R. Solving large structured Markov Decision Problems for perishable inventory management and traffic control / R. Haijema; Dissertation, Amsterdam. University of Amsterdam (UvA). – URL: https://pure.uva.nl/ws/files/4314821/59982_thesis.pdf (accessed at: 25.04.2022).
[42] Pierskalla, W.P. Optimal Issuing Policies for Perishable Inventory / W.P. Pierskalla, C.D. Roach // Management Science. – 1972. – Vol. 18. – N 11. – P. 603–614.
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The main areas of resilience research in logistics and supply chain management are assessing the impact of supply chain structure, using different methods to mitigate the negative impact of disruptions, and preparing the supply chain for possible negative consequences. Thus, resilience is formed at several interrelated levels: structure, processes, and operations. More recent research papers have focused on the study of resilience in the context of modern digital technology.

The system's feedback formed by the ripple effect makes possible comparison with another well-known phenomenon in supply chain dynamics – the "bullwhip effect"[45]. For example, controlled experiments based on the "MIT beer game" [46,47] business simulator are used to analyze supply chain participants' behavior and coordinate the dissemination of information about a supply chain disruption. These research works detailed the value of supply-side information sharing to reduce the impact of disruption on the growth of the supply chain bullwhip effect.

Promising directions for research on the ripple effect: the relationship of the network structure of supply chains and optimal ways to reduce the impact of the ripple effect, modeling the spread of the negative impact of disruption in multi-echelon supply chains, the interconnection of the ripple effect and other factors of uncertainty. The limited shelf life factor has a significant impact during the supply chain recovery phase after a disruption. However, it has not been addressed in detail in the early work on supply chain resilience. In addition, much of the research focuses on supply chain disruption prevention and mitigation during an adverse risk event. However, the process of supply chain stabilization has been studied to a lesser extent (Figure 1).

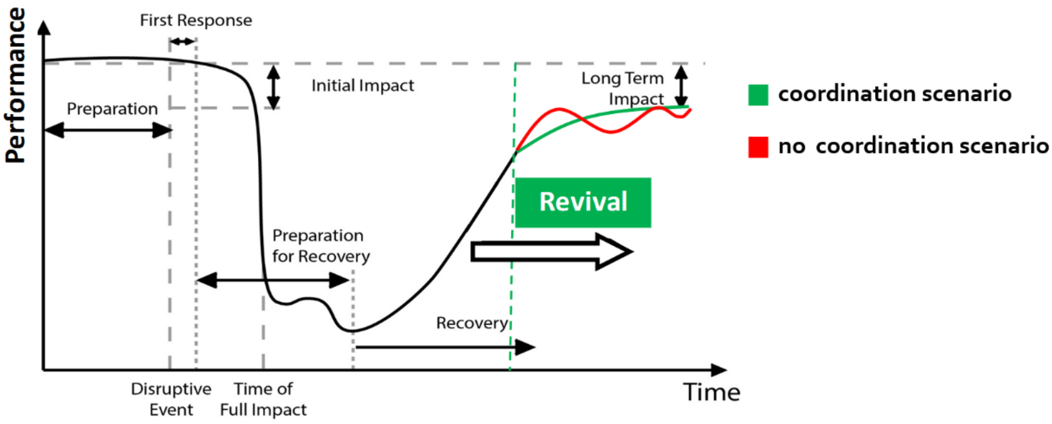

Figure 1 – Stages of the impact of a negative risk event on supply chain operations

Source: developed by the author.

[45] Sterman, J.D. Business Dynamics: Systems Thinking and Modeling for Complex World / J.D. Sterman; – Boston: McGraw-Hill, 2000. – 1008 p.

[46] Sarkar, S. A Behavioral Experiment on Inventory Management with Supply Chain Disruption / S. Sarkar, S. Kumar // International Journal of Production Economics. – 2015. – Vol. 169 (C). – P. 169–178.

[47] Forrester, J. Industrial Dynamics A Major Breakthrough for Decision Makers/ J. Forrester // Harvard Business Review. – 1958. – Vol. 36. – P. 37–66.

To the author's knowledge, this dissertation research is the first in the following components:

1. The concept of postponed redundancy is formulated, and metrics for evaluating the supply chain stabilization process are analyzed;
2. The research shows that the ripple effect can be a driver of the bullwhip effect and that the emergence of the bullwhip effect can be caused by a significant disruption, even though the spread of the disruption impact is directed toward supply chain customers;
3. The specifics of the propagation of the ripple effect under different inventory depletion policies of products with a limited shelf life are considered.

The **research object** is studying the supply chains of food products manufacturing companies and retailers.

The **research subject** refers to the supply chain ripple effect impact on inventory management system parameters of food manufacturers and retail companies.

The **research goal** is to optimize the parameters of the inventory management system for products with limited shelf life by leveling the effects of the ripple effect.

In order to achieve this goal, the following **research tasks** were established and implemented:

1. To analyze the theoretical developments of domestic and foreign researchers devoted to the ripple effect in supply chains and resilience of supply chains;
2. To develop and to test a simulation model that combines the agent-based and discrete-event approaches to assess the impact of the ripple effect;
3. To analyze the impact of the order cycle on supply chain performance after a disruption ends and to identify metrics to track this impact;
4. To identify the relationship between the ripple effect and the "bullwhip effect" and to develop metrics to describe this type of interaction;
5. To analyze the effectiveness of inventory management to reduce the impact of the ripple effect in the supply chain of products with limited shelf life under different supply chain configurations and different inventory shipment policies.

Methodology & Methods. Theoretical developments of domestic and foreign researchers, discrete event simulation, agent-based simulation are used.

To solve the first problem, the works devoted to supply chain resilience issues and approaches to supply management of products with a limited shelf life were analyzed. The works indexed in the interdisciplinary databases of scientific citation Web of Science and Scopus were considered. A review of the literature showed that the final phase of the impact of supply chain disruption is a less studied area of research.

A supply chain model of products with a limited shelf life was developed in the AnyLogic simulation modeling environment to solve the second problem. The model uses a combined approach that incorporates elements of discrete-event and multi-agent modeling. The model has a modular structure with the possibility of modification and has been consistently refined to work with different research problems. The model can be adapted for both retail companies (retail networks) and manufacturing companies.

To solve the third problem, the model was adapted to the case of the FMCG company, and several experiments with this model under different operating conditions were conducted. The study allowed for the first time to identify the specifics of the limited shelf life products supply chain functioning under conditions of possible supply chain disruptions. Supply chain functioning during the impact of disruption can be divided into several consecutive stages. This study focuses on the supply chain recovery period when the affected facility is functioning normally again, but the supply chain dynamics are still different from the normal operating mode. Metrics for tracking this state are defined.

To solve the fourth problem some additional experiments were conducted with the developed simulation model. The study was the first to consider the relationship between the bullwhip effect and the ripple effect in supply chains. The main possible scenarios of the influence of these effects on each other were described, and indicators were formulated to measure this influence quantitatively.

To solve the fifth problem, the simulation model was adapted to the case of a supply chain of a retail company to study additional characteristics of the ripple effect propagation. The two-echelon version of the model was modified and expanded: another distribution network echelon and a parallel supply chain loop were added to the supply chain, which can be used as an alternative source of supply. The supply planning algorithm has been redesigned: the possibility of using different inventory shipment policies has been added. These changes made it possible to evaluate the impact of the logistics network configuration, the implementation of the planning algorithm, and the inventory shipment policy on the propagation of the ripple effect within the supply chain. Also, for the first time, the specifics of the supply chain disruption effect when using different inventory shipment policies were examined.

The author obtained the following **main findings to be defended**:

1. The characteristics of the recovery process for the supply chains of limited shelf life products, affecting supply chain performance, were determined;
2. The ripple effect and the bullwhip effect in supply chains are interrelated, this relationship can be quantified;

3. The dependence of the ripple effect propagation on the inventory depletion policy used under various configurations of the logistics network was determined.

Thesis research contains the following elements of **scientific novelty**:

1. Research analysis has shown that supply chain disruption models with consideration of product shelf life constraints is an understudied area;
2. Base model and its modifications have been developed to assess the impact of limited shelf life products supply chain disruptions under different configurations of logistics networks;
3. For the first time by means of simulation, the main features of resilience characteristics of supply chains of products with a limited shelf life were revealed – the concept of “postponed redundancy” was defined;
4. For the first time, the mutual influence of the bullwhip effect and the ripple effect during supply chain disruption and supply chain recovery were identified using simulation, and metrics were formulated to quantify this type of influence;
5. The effect of different inventory depletion and processing policies on the propagation of the ripple effect in case of supply chain disruptions with partial loss of capacity has been analyzed.

The theoretical significance of the thesis research involves its contribution to:

1. For the first time the role of limited shelf life in the context of supply chain resilience is considered and the effect of "postponed redundancy" is defined. This effect makes it possible to quantify the impact of coordination of production management and order placement policies both during the impact of a negative risk event and immediately after its termination during the process of restoration of the normal functioning of the supply chain. An approach to the evaluation of indicators that makes it possible to track the stages of the impact of the consequences of a supply chain disruption is proposed;
2. To the author’s knowledge, this is the first study to examine the interaction of the ripple effect and the bullwhip effect in the context of products with limited shelf life, stochastic demand, inventory management policies, production batch management policies, and disruptions in the supply chain. In addition, for the first time, a metric is proposed to estimate the effect of the ripple effect on the bullwhip effect.

The practical significance of the thesis research refers to:

1. To meet the research objectives, a hybrid simulation model was developed, combining elements of discrete-event and multi-agent modeling. A scenario analysis of individual

model configurations was performed, as well as a search for optimal values of model parameters;

2. The study examined methods of reducing write-offs while maintaining supply chain resilience under conditions of limited product shelf life in supply chain planning with possible production disruptions;
3. Analysis of the dynamics of the impact of adverse risk events on the overall performance of the supply chain of products with a limited shelf life was performed.

Approbation of the Thesis Research Results. The results of the thesis research were presented by the author and discussed at international conferences:

16th IFAC (International Federation of Automatic Control) Symposium on Information Control Problems in Manufacturing (June 11–13, 2018, Bergamo, Italy). Presentation: "Contingency production-inventory control policy for capacity disruptions in the retail supply chain with perishable products.

9th IFAC (International Federation of Automatic Control) Conference MIM 2019 on Manufacturing Modeling, Management, and Control. (28–30 August 2019, Berlin School of Economics and Law, Berlin, Germany). Presentation: “Disruption Tails and Post-Disruption Instability Mitigation in the Supply Chain”.

The following **limitations** should be taken into account while generalizing and summarizing the results:

1. The main sequential events in the model related to the negative impact of a supply chain disruption are distributed over time. In the case of products with a limited shelf life, there is an increase in inventories after the direct impact of the disruption is eliminated. Increased inventory levels lead to increased write-offs risks. For these reasons, it takes several periods for the system to stabilize. When analyzing the performance of the simulation model, it is possible to track which orders placed during the recovery period of the supply chain led to the following write-offs due to expired shelf life. In real life, such a retrospective analysis can be applied to a limited extent;
2. System performance analysis during a disruption and recovery period does not fully account for future dynamics, such as expected write-off periods. Thus, supply chain disruptions and write-off dates can be considered as factors in the importance of studying supply chain dynamics. Additional research is required to study multi-product and multi-echelon supply chains. Better supply planning algorithms, as well as other types of supply chain disruption profiles, are also important research areas;

3. Supply chains with the same types of supply for each link in the network were considered in the research. The analysis of the dynamics in the joint application of multiple types of supply (storage, cross-docking) and various options for centralizing the decision-making in the inventory management algorithms applied are promising areas for further research.

2. MAIN FINDINGS TO BE DEFENDED

1. The characteristics of the recovery process for the supply chains of limited shelf life products, affecting supply chain performance, were determined.

The study of the supply chain recovery period after the end of the immediate impact of an adverse risk event (e.g., restoring production capacity to 100% after a 50% reduction) allowed us to formulate the following statements:

1. Without coordinated action after the end of a supply chain disruption, increased inventory costs are generated due to delivering products that were not shipped on time earlier during the disruption period.

This effect can be referred to as “postponed redundancy”. In this case, the consequences of disruption are product shortages and write-off risks at the same time. Supply chains with a long cycle between order placement and delivery are more vulnerable to the negative impact of supply chain disruptions (Figure 2).

2. Lack of coordinated behavior of chain links during a disruption leads to excessive orders as a “panic” response.

Coordinating algorithms are required to monitor supply chain behavior, identify disruptions, and adjust ordering rules (Figure 3).

3. Cancellation of orders placed during the disruption period immediately after the end of the risk event avoids excess inventory and write-off risks.

When using the coordinated policy, the stock level during the recovery period is not higher than that during the regular operation period.

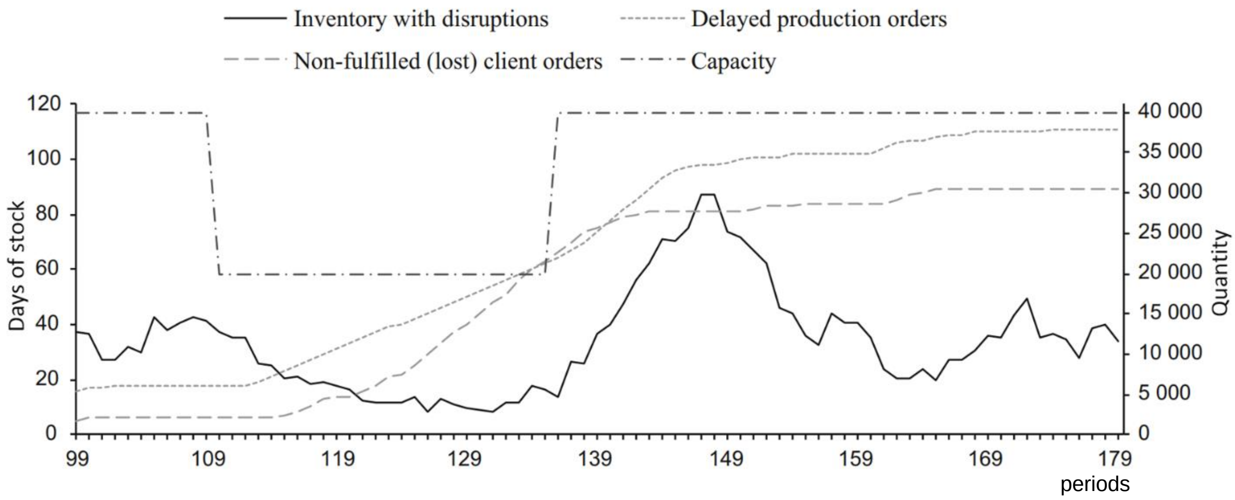

Figure 2 – The effect of lack of coordination after the end of a negative risk event[48]

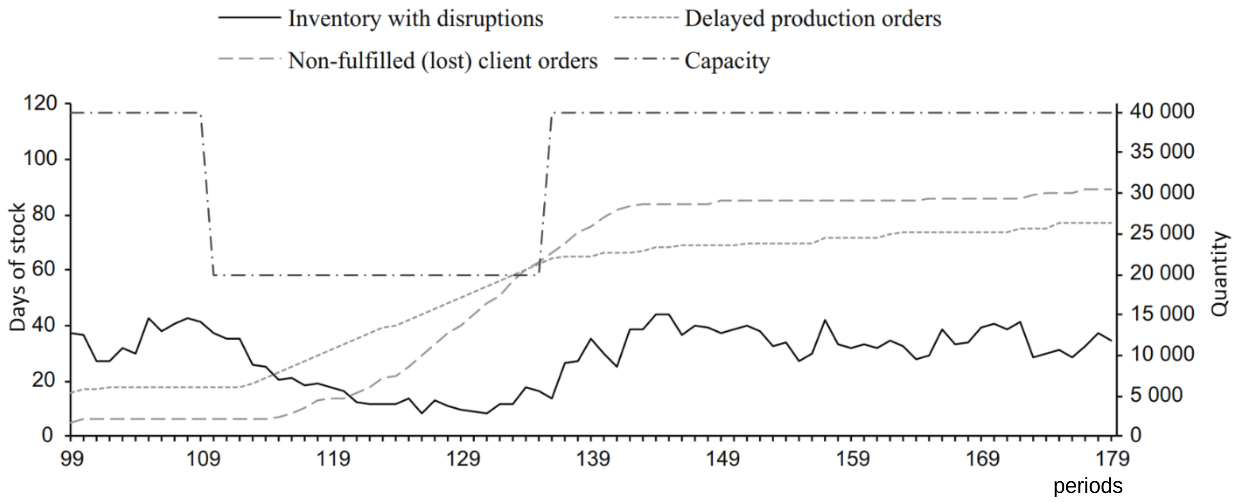

Figure 3 – The effect of coordination after the end of a negative risk event[48]

4. After returning to regular operation, the average inventory level and the dynamics of canceled orders can be used as indicators of supply chain recovery.

Unfulfilled orders are one indicator of supply chain inertia. In this case, inertia refers to the duration of the feedback loop in the supply chain. If the number of this type of orders increases despite a stabilized level of service, it indicates that a significant increase in inventory is imminent.

The following generalization of the obtained results can be made based on the analysis of experiments:

1. Supply chains with long cycles between order placement and delivery are more susceptible to the adverse effects of disruptions;

[48] Source: Rozhkov, M. Coordination of production and ordering policies under capacity disruption and product write-off risk: an analytical study with real-data based simulations of a fast moving consumer goods company / D. Ivanov, M. Rozhkov // Annals of Operations Research. – 2020. – N 291. – P. 387–407.

2. Cancellation of orders not fulfilled on time (and informing about the end of the impact of the risk event) leads to lower inventory levels and write-off risks while maintaining the service level;
3. If the number of orders not completed on time increases despite the stabilization of the service level, it indicates an anticipated surge in inventory levels;
4. The higher the frequency of order placement and the lower the minimum order size (within the limits defined by experiments), the higher the flexibility of the supply chain. The actual order size is defined as a multiple of the minimum order size.

The average supply chain inventory level cannot be used as the only indicator of supply chain performance during a disruption. But in combination with the dynamics of canceled orders, it can be used during the recovery phase of the supply chain. Orders not fulfilled on time are one of the indicators of system inertia. If there is an increase in this indicator, there may be a significant increase in the inventory level.

2. The ripple effect and the bullwhip effect in supply chains are interrelated, this relationship can be quantified.

Lack of coordination in the supply chain during a disruption causes a bullwhip effect in spreading the consequences of a risk event forward along the supply chain (toward the end consumer). During a disruption, placing excessive orders can be seen as a “panic” response. Supply chain activities change during the disruption period, resulting in unfulfilled orders, changes in production, order placement, and inventory management policies. These changes may persist beyond the end of the risk event. For this reason, it is essential to develop specific policies to restore and stabilize the supply chain during the transition from one state to another.

Coordination of the supply chain during periods of disruption avoids the emergence of a bullwhip effect when the ripple effect caused by a disruption occurs (Figure 4, Figure 5). In addition, these measures help to stabilize inventory levels and reduce the number of shortages. Adjustment (adaptation) can be performed in two ways. The first way is the cancellation of orders not fulfilled in time during the restoration of the normal mode of operation. The second is the suspension of placing new orders, even if the inventory level is below the specified level during the risk event.

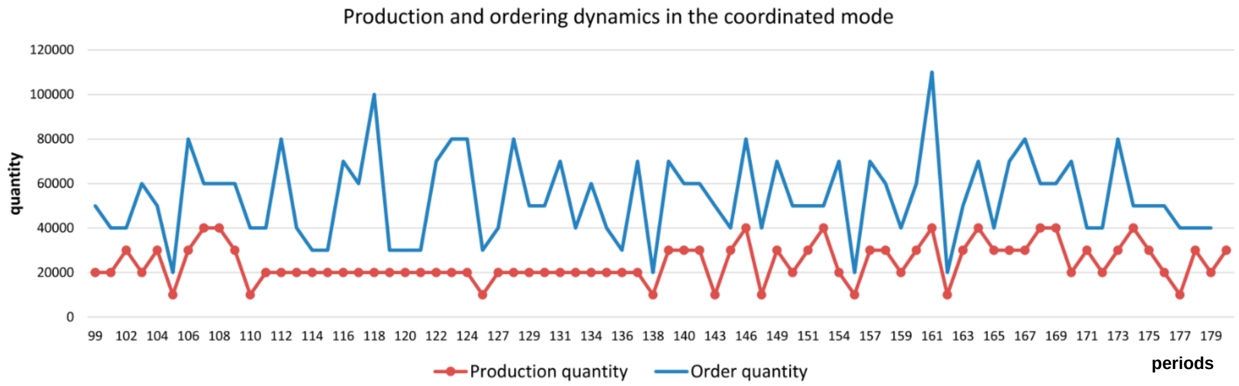

Figure 4 – Dynamics of production and orders under the coordination[49]

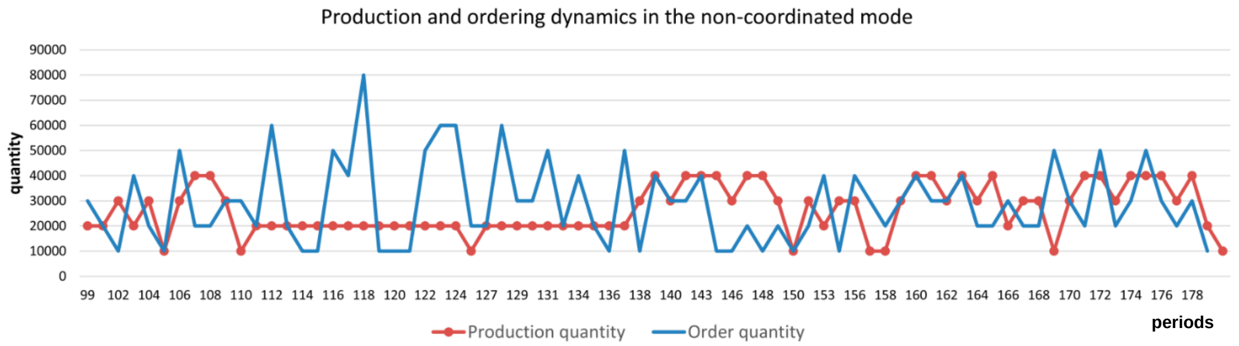

Figure 5 – Dynamics of production and orders under lack of coordination[49]

A formula is proposed to estimate how the ripple effect can serve as a driver for the bullwhip effect. This formula is based on an approach for numerically estimating the bullwhip effect[50]. An estimate of order variation ($OrderVarR$) can be calculated as follows (1):

$$OrderVarR = \frac{\sigma^2_{order}/\mu_{order}}{\sigma^2_{demand}/\mu_{demand}} \qquad (1)$$

In this formula, μ corresponds to the average demand or average order size. The value of the standard deviation is denoted by σ. Obviously, if the ratio is greater than one, there is a bullwhip effect. If the ratio is equal to one, there is no bullwhip effect. If the level is less than one, the bullwhip effect fades.

One of the main characteristics of the ripple effect is the change in the level of performance of the supply chain participants. An increase in supply variation increases the uncertainty in

[49] Source: Rozhkov, M. Does the ripple effect influence the bullwhip effect? An integrated analysis of structural and operational dynamics in the supply chain / A. Dolgui, D. Ivanov, M. Rozhkov // International Journal of Production Research. – 2020. – Vol.58. – N 5. – P. 1285–1301.
[50] Disney, S.M. On the Bullwhip and Inventory Variance Produced by an Ordering Policy / S.M. Disney, D.R. Towill // Omega. – 2003. – Vol. 31. N 3. – P. 157–167.

planning in the supply chain. Therefore, the approach based on the assessment of supply and demand variation can be used to estimate the ripple effect, taking into account supply variation (2):

$$SupplyVarR = \frac{\sigma^2_{supply} / \mu_{supply}}{\sigma^2_{demand} / \mu_{demand}} \quad (2)$$

A significant difference between the ripple effect and the bullwhip effect is that the dynamics of the ripple effect during propagation along the supply chain echelons is not always increasing. The relationship between orders and deliveries makes it possible to assess the performance of the supply chain and thus quantify the impact of the ripple effect[51]. Moreover, an estimate of order fulfillment objectively characterizes the propagation of disruption or the ripple effect. The relationship between supply and order variation is represented by the following formula, which allows us to estimate the extent to which the ripple effect and the bullwhip effect mutually influence each other (3).

$$Index^{RE}_{BWE} = \frac{SupplyVarR}{OrderVarR + SupplyVarR} \quad (3)$$

If $Index^{RE}_{BWE}$ value is within range {0, 1}, then there is an influence of the ripple effect on the bullwhip effect. The closer the value of $Index^{RE}_{BWE}$ is to one, the proportionally higher the influence of the ripple effect on the bullwhip effect. If $Index^{RE}_{BWE} = 0$, then there is no influence of the ripple effect on the bullwhip effect.

For the first time, it is shown that the ripple effect can be a driver of the bullwhip effect and that the bullwhip effect can be triggered by a significant disruption, even though the spread of the consequences of the disruption goes forward along the supply chain. Thus, this risk must be taken into account both at the time of the adverse event and shortly after that. The structural dynamics of supply chains affect policies for inventory management, production management, and order placement.

Generation of excess orders during a supply chain disruption is possible if production does not inform about the disruption and new capacity constraints imposed by it. For this reason, new orders appear in the system every period. These orders overload the production that is not operating at full capacity due to the disruption.

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[51] Ivanov, D. Structural Dynamics and Resilience in Supply Chain Risk Management / D. Ivanov; – New York: Springer, 2018. – 320 p.

After the disruption ends, the production that has reached baseline capacity fulfills these excess orders, which leads to a sharp increase in the inventory level of the distribution network links after production. The frequency of order placement then changes again. High inventory levels lead to product write-offs, and so the number of orders decreases. In the case of under-deliveries to customers, there may be additional penalties. Thus a production disruption can cause a bullwhip effect. This statement is also true for products without a limited shelf life.

3. The propagation of the ripple effect under different configurations of the logistics network depends on the inventory depletion policy used.

To analyze the impact of this type, several configurations of product shipment policies, several network options, and several types of inventory depletion policies were formulated and modelled. Each design implied a different set of actions in the event of a supply chain disruption.

Experiments with the simulation model allowed us to evaluate the impact of different depletion policies under different supply chain configurations at different levels:

1. Logistics network level: two parallel networks with the same interchangeable products;
2. Process level: two options for inventory handling in the distribution center (storage and cross-docking);
3. Process level (product): limited shelf life, different inventory depletion policies in distribution centers;
4. Operational level: change in the source of supply.

The impact of inventory depletion policy is more pronounced during the initial stage of a supply chain disruption. During the recovery period of the supply chain, the depletion policy has less impact (Figure 6).

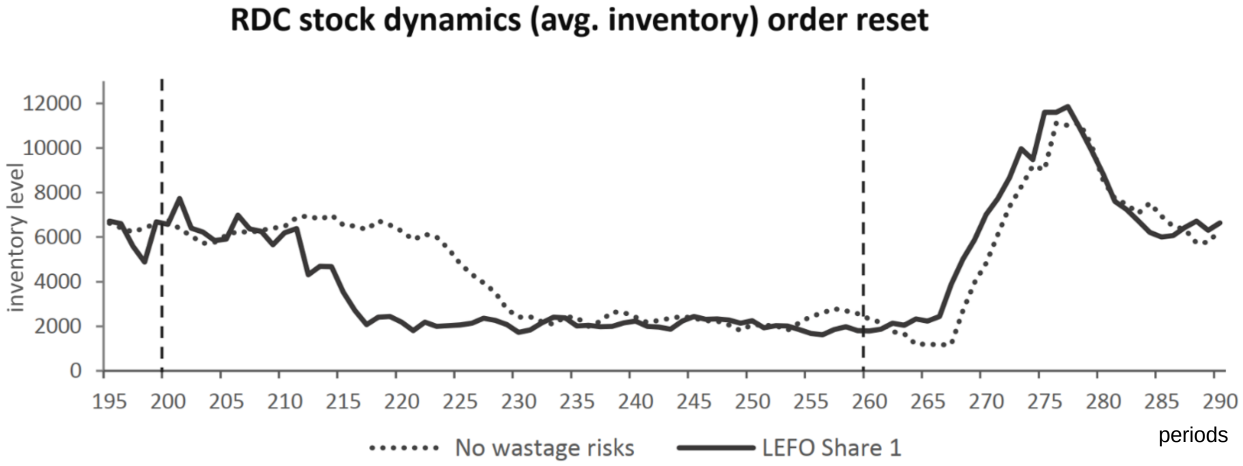

Figure 6 – Dynamics of inventory level at different restrictions on the remaining shelf life of products[52]

Supply chains of products with a limited shelf life cope more effectively with the impact of a risk event when there is an alternative source of supply (Table 1). It is possible to quickly switch the supply source if the logistics network is sufficiently developed or if there is a parallel contour (for example, in the case of several logistics networks of a group of companies under unified management). In this case, in the case of partial loss of supply chain capacity, the period of switching to an alternative source of supply is not the most critical.

Table 1 – The Effect of Supply Source Rerouting Delay Time on Supply Chain Performance[53]

Network configuration	Rerouting delay, periods	Total Costs, $	Out of Stock Costs, $	Wastage Costs, $	Service Level, %
FDC Stock	0	192 808 360	–	1 111 792	100%
FDC Stock	10	192 698 154	2 000	859 971	99.90%
FDC Stock	20	192 989 102	36 000	883 635	99.80%
FDC Cross-docking	0	208 593 908	3 000	6 165 150	99.90%
FDC Cross-docking	10	209 400 811	33 000	6 350 767	99.90%
FDC Cross-docking	20	210 628 878	184 000	6 510 463	99.20%

[52] Source: Rozhkov, M. Supply chain ripple effect: impact of disruption profile and priority scheduling rules for perishable inventory / M. Rozhkov // International Journal of Integrated Supply Management. – 2022. – Vol.15. – N 2. – P. 184–205.
[53] Source: Rozhkov, M. Supply chain ripple effect: impact of disruption profile and priority scheduling rules for perishable inventory / M. Rozhkov // International Journal of Integrated Supply Management. – 2022. – Vol.15. – N 2. – P. 184–205.

3. CONCLUSIONS

The dissertation research analyzes the resilience of supply chains of products with a limited shelf life. These supply chains are characterized by the fact that not all basic approaches to improving their resilience are applicable. The added inventory dimension in the form of remaining shelf life significantly complicates the product shipment planning process and also increases the susceptibility of the supply chain to external negative impacts in general. When the supply chain for products with a limited shelf life is hit by a disruption, the impact of the resulting dynamic effects can destabilize the system and simultaneously increase both the risks of product write-offs and the risks of shortages.

One of the effects associated with the dynamic characteristics of resilience is the ripple effect. A hybrid simulation model combining elements of discrete-event and multi-agent modeling approaches is used as a research tool. This method is effectively used for solving research problems, as it allows to manage the degree of detailing of the described systems, includes possibilities of additional optimization, and also provides an opportunity to integrate the algorithm for supply planning into the model. Thus, both the problems of inventory management and the problems of increasing the supply chain resilience are simultaneously considered.

This study formulates the concept and presents the mechanism of emergence of one of the components of the ripple effect: “postponed redundancy”. Metrics are analyzed and approaches are formulated to track this phenomenon. It is shown that the negative consequences of “postponed redundancy” can be corrected by additional control measures, coordination of actions between the links of the supply chain during the stage of recovery after the end of the disruption impact.

For the first time the mutual influence of two dynamic effects in supply chains has been considered: the ripple effect and the bullwhip effect. Although these effects have different genesis and often propagate through the supply chain in opposite directions, there are scenarios in which they will be mutually reinforcing. A metric for the numerical estimation of the dynamics of propagation of these effects in the supply chain in aggregate is proposed.

Additionally, the specifics of supply chain functioning with different logistics network configurations, inventory handling policies, and inventory shipment policies are considered. For the first time, the effects of basic inventory shipment policies on the propagation of supply chain disruption effects are compared. Thus, the parameters for improving supply chain resilience at three main levels are considered: process control, operational control, and logistics network structure.

4. LIST OF AUTHOR'S PUBLICATIONS

The main results of the thesis research are presented in the three articles published in the international peer-review journals indexed in multidisciplinary citation databases Scopus and Web of Science (WoS):

1. Rozhkov, M. Coordination of production and ordering policies under capacity disruption and product write-off risk: an analytical study with real-data based simulations of a fast moving consumer goods company / D. Ivanov, M. Rozhkov // Annals of Operations Research. – 2020. – N 291. – P. 387–407 (Scopus Q1 Management Science and Operations Research[54], WoS Q1 Operations research & management science[55]).

The author of the dissertation research was responsible for the empirical part of the article, including data preparation, development and description of the simulation model, and conducting the experiments. The author also participated in the selection and analysis of the relevant literature. The results formed the basis for the first, second, and third tasks of the thesis research.

2. Rozhkov, M. Does the ripple effect influence the bullwhip effect? An integrated analysis of structural and operational dynamics in the supply chain / A. Dolgui, D. Ivanov, M. Rozhkov // International Journal of Production Research. – 2020. – Vol.58. – N 5. – P. 1285–1301 (Scopus Q1 Management Science and Operations Research[56], WoS Q1 Operations research & management science[57]).

The author of the dissertation research was responsible for the empirical part of the article, including data preparation, development and description of the simulation model, and conducting the experiments. The author also participated in the selection and analysis of the relevant literature. The results formed the basis for the first, second, and fourth tasks of the thesis research.

3. Rozhkov, M. Supply chain ripple effect: impact of disruption profile and priority scheduling rules for perishable inventory / M. Rozhkov // International Journal of Integrated Supply Management. – 2022. – Vol.15. – N 2. – P. 184–205 (Scopus Q3 Strategy and Management[58]).

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[54] URL: https://www.scimagojr.com/journalsearch.php?q=23090&tip=sid&clean=0 (accessed at: 25.04.2022).
[55] URL: https://jcr-clarivate-com/jcr-jp/journal-profile?journal=ANN%20OPER%20RES&year=2020&fromPage=%2Fjcr%2Fbrowse-journals (accessed at: 25.04.2022).
[56] URL: https://www.scimagojr.com/journalsearch.php?q=27656&tip=sid&clean=0 (accessed at: 25.04.2022).
[57] URL: https://jcr-clarivate-com/jcr-jp/journal-profile?journal=INT%20J%20PROD%20RES&year=2020&fromPage=%2Fjcr%2Fbrowse-journals (accessed at: 25.04.2022).
[58] URL: https://www.scimagojr.com/journalsearch.php?q=3900148211&tip=sid&clean=0 (accessed at: 25.04.2022).

The author of the thesis research is the sole author of the article and is fully responsible for all the conclusions presented in this work. The obtained results formed the basis for solving the dissertation research's first, second, and fifth tasks.

In addition, the results of the thesis research are reflected in the following publications:

1. Rozhkov, M. Adapting supply chain operations in anticipation of and during the COVID-19 pandemic / M. Rozhkov, D. Ivanov, J. Blackhurst, A. Nair // Omega. – 2022. – Vol.110. – N 9(102635). – P. 2–49 (Scopus Q1 Management Science and Operations Research[59], WoS Q1 Operations Research & Management Science[60]).

2. Rozhkov, M. Contingency production-inventory control policy for capacity disruptions in the retail supply chain with perishable products / M. Rozhkov, D. Ivanov // 16th IFAC Symposium on Information Control Problems in Manufacturing INCOM. – 2018. – Vol. 51. – N 11. – P. 1448–1452.

3. Rozhkov, M. Disruption Tails and Post-Disruption Instability Mitigation in the Supply Chain / M. Rozhkov, D. Ivanov // 9th IFAC (International Federation of Automatic Control) Conference MIM 2019 on Manufacturing Modeling, Management, and Control. – 2019. – Vol. 52. – N 13. – P. 343–348.

4. Rozhkov, M. Disruption Tails and Revival Policies in the Supply Chain / M. Rozhkov, D. Ivanov // Handbook of Ripple Effects in the Supply Chain. International Series in Operations Research & Management Science. – 2019. – Vol. 276. – P. 229–260.

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[59] URL: https://www.scimagojr.com/journalsearch.php?q=21915&tip=sid&clean=0 (accessed at: 25.04.2022).
[60] URL: https://jcr-clarivate-com/jcr-jp/journal-profile?journal=OMEGA-INT%20J%20MANAGE%20S&year=2020&fromPage=%2Fjcr%2Fhome (accessed at: 25.04.2022).