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New disruption risk management perspectives in supply chains: digital twins, the ripple effect, and resileanness

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Abstract: This paper aims at delineating major features of the two new perspectives in supply chain (SC) disruption risk management, i.e., ripple effect and resileanness. The methodologies to mitigate the SC disruptions and recover in case of severe disruptions are discussed. It observes the reasons and mitigation strategies for the ripple effect in the SC and presents the ripple effect control framework that is comprised of redundancy, flexibility, and resilience. Even though a variety of valuable insights has been developed in the given area in recent years, new research avenues and ripple effect taxonomies are identified for the near future. The special focus is directed towards the supply chain risk analytics for disruption risks and the ripple effect in digital supply chains. In particular, the digital SC twin framework is presented.

Keywords: supply chain, resilience, disruption, ripple effect, digital supply chain, digital twin, blockchain, Industy 4.0, risk analytics

1. RIPPLE EFFECT

Disruption risks represent a new challenge for supply chain (SC) managers when designing and managing resilient SCs (Ivanov and Arkhipov 2011, Klibi and Martel 2012, Spiegler et al. 2012, Ivanov et al. 2013, Mizgier et al. 2013, Ambulkar et al. 2015, Yildiz et al. 2016, Ivanov et al. 2014a,b, Fahimnia et al. 2015, Ho et al. 2015, Govindan et al. 2016, Schmitt et al. 2017, Sawik 2017, Rezapour et al. 2017, Ivanov 2018a, Dolgui et al. 2018, Ghavamifar et al. 2018, He et al. 2018, Macdonald et al. 2018, Song et al. 2018). In many cases, we face the *ripple effect* when considering SC disruptions. The ripple effect occurs when a disruption, rather than remaining localized or being contained to one SC part, cascades downstream and impacts the performance of the SC (Ivanov et al. 2014a,b, Han and Shin 2016, Sokolov et al. 2016, Akkermans, and van Wassenhove 2017, Dolgui et al. 2018, Ivanov 2017a,b, 2018a,b, Levner and Ptuskin 2018, Oiha et al. 2018, Pavlov et al. 2018, Scheibe and Blackhurst 2018, Dubey et al. 2019, Hosseini et al. 2019a,b, Ivanov et al. 2019a,b). This impact might include lower revenues, delivery delays, loss of market share and reputation, and stock return decreases— the cost of all of which could be devastating.

Ripple effect causes structural changes in the SC. The main supply chain features is the multiple structure design and changeability of structural parameters because of objective and subjective factors at different stages of the SC life cycle. In other words, supply chain *structural dynamics* is constantly encountered in practice (Ivanov and Sokolov 2010, Ivanov et al. 2010, 2017a,b,c, Ivanov 2018a, 2019a,b).

One of the main objectives of SC disruption risk management is therefore and control structural dynamics to increase total SC performance. At the same time, achievement of planned performance can involve the impact of disruptions in a real-time execution environment. SC execution is subject to uncertainty at the planning stage and disruption at the execution stage. Cost efficiency comes with a huge hidden expense should a major disruption (i.e., a more severe impact than a routine disturbance) occur. This requires SC protection against and efficient reaction to disturbances and disruptions. Therefore, supply chains need to be planned to be *stable, robust and resilient* enough to (1) maintain their basic properties and ensure execution; and (2) be able to adapt their behavior in the case of disturbances in order to achieve planned performance using recovery actions.

Resilient SC design extends traditional SC design approaches with regard to the incorporation of redundancies such as back-up facilities, inventory and capacity flexibility. These redundancies create, at the proactive planning stage, some flexibility that can be used at the reactive control stage in the case of disruptions in SC structures in order to recover system performance and operational processes.

There is a strong and growing literature on robustness and resilience as two fundamental concepts to analyze SC performance with severe uncertainty consideration and with regards to scattered disruptive events resulting in SC structural dynamics. A SC is called *robust* if it is able to absorb disturbances and continue execution with minimal impact on performance. The performance of such a SC is insensitive to the negative impacts of disruptions (Ivanov and Sokolov 2013, Cavalcentia et al. 2019, Hosseini et al. 2019a,b, Yoon et al. 2018, Lücker et al. 2019, Pavlov 2019, Ivanov and Sokolov 2019). At the same time, we may distinguish between *being safe* and *performing safely*. In contrast to robust-

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ness that considers proactive redundancy (e.g., buffer capacities, backup suppliers, or risk mitigation inventory) at the pre-disruption stage, *resilience* deals with the system's ability to sustain or restore its functionality and performance following a significant change in the system and environment conditions (Tang 2006, Aven 2017). As such, an integration of pro- and reactive decisions is important for increasing SC resilience by utilizing the synergetic effects between mitigation and contingency policies.

According to the ripple effect control framework (Dolgui et al. 2018) and other literature on the disruption propagation in the SC (e.g., Scheibe and Blackhurst 2018), disruption risks and their propagation in the SC are mainly caused by single sourcing, low risk mitigation inventory, overutilization of capacities, and missing contingency plans.

The width of the ripple effect and how it impacts economic performance is reliant on redundancies such as inventory or capacity buffers, also called robustness reserves, and on the speed and extent of recovery measures. As a result, it is necessary that, in the proactive mode, risk and SC resilience are assessed and incorporated at the design and planning stages. In the reactive mode, operationalization of contingency plans, such as alternative suppliers or shipping routes, must occur quickly in the control stage.

Ripple effect control in the SC requires two critical capacities: resistance and recovery. For resistance, which is the SC's ability to protect against disruptions and reduce impact once the disruption occurs, some redundancy such as backup sourcing, risk mitigation inventory or capacity flexibility must be built in at the proactive stage. For recovery, this redundancy must be activated jointly with reactive contingency plans with regards to risk mitigation inventory, capacity flexibility and backup sources.

Robustness reserves can include material inventory, capacities buffers, etc. Increase in inventory, additional production capacities, and alternative transportation methods or back-up facilities would increase costs. At the same time, these so-called redundant elements would potentially lead to an increase in sales and service level. Redundancy elements may also increase supply chain flexibility and have positive effects on both service level and costs. The resilient state of a SC requires a balanced robustness and flexibility which allows for achieving maximum performance with disruption risk considerations at acceptable redundancy costs.

While ripple effect and disruption risks has attracted considerable research attention, this research domain seems to be at the beginning stage of development. Some future research avenues are summarized in this section. With regards to the current research, we refer the readers to recent state-of-the-art survey in the given domain for more detailed analysis (Ho et al. 2015, Fahimnia et al. 2015, Ivanov et al. 2017c, Dolgui et al. 2018, Hosseini et al. 2019a).

2. RISK ANALYTICS AND INDUSTRY 4.0

Innovations in digital technologies influence the development of new paradigms, principles, and models in SCs. The Internet of Things (IoT), cyber physical systems, additive manufacturing, and smart, connected products, facilitate the development of Industry 4.0-driven digital SC (Ivanov et al. 2016, 2019b). Such technology advances are facilitated by the advent of big data analytics, and advanced tracking and tracing technologies. Accompanying such technological advances are similar advances in organizational practice and culture, shaped by socio-technical considerations of new technology use. The dynamic nature of digitalization demands research that can help analyze, understand, and evaluate its drivers, facilitators, and performance outcomes, Such outcomes could range from time competitiveness to risk management and resilience.

The impact of digitalization on resilient operations and the SC can be quite complex. Consider some interplays. Risk in the SC can be mitigated by the descriptive and predictive use of big data analytics in gaining visibility and forecast accuracy, reduction in information disruption risks, and improved contingency plan activation. Reductions in supply and time risks can be achieved by using advanced trace & tracking systems leading to real-time coordinated activation of contingency policies.

SCs typically hedge against disruptions by means of risk mitigation inventory, capacity reservations and backup sources. Such protection is expensive to maintain (in anticipation), and deploy. Block-chain digitalization could help reduce risk and associated preventive costs, if a record of activities and data needed for recovery exists for synchronized contingency plans. Similarly, additive manufacturing can reduce the need for risk mitigation inventory and capacity reservations, as well as diminish the need for expensive backup contingent suppliers. The decentralized control principles in Industry 4.0 systems make it possible to diversify risks and reduce the need for structural SC redundancy with the help of manufacturing flexibility. Big data analytics and advanced trace & tracking systems in general, and blockchain technology in particular, can help us to trace the roots of disruptions, to observe disruption propagation (i.e., the ripple effect) (Dolgui et al. 2018, Ivanov et al. 2019a), to select short-term stabilization actions based on a clear understanding of what capacities and inventories are available (emergency planning), to develop mid-term recovery policies, and to analyse the long-term performance impact of ripples effects. Additive manufacturing has a potential to reduce disruption propagation in the SC, since the number of SC layers and the resulting complexity would be reduced. Resilience may improve, resultantly.

Initial efforts to understand the impact of digital technologies on the SC risk management are underway. However, both conceptual and granular understandings of the contribution and the interplay of different digital technologies in regard to specific SC and operations resilience and sustainability requires further analysis.

The impact of digitalization and Industry 4.0 on the ripple effect and disruption risk control analytics in the SC is therefore a promising research avenue. The purpose of the research in the given are is to investigate the interplay between digitalization, SC resilience, and SC risks. The scope synthesizes research from two distinct areas, i.e., the impact of digitalization on logistics, and the impact of SC management on risk control. As such, the topics of this domain connect business, information, engineering and quantitative analysis perspectives on digitalization to control and the SC risks issues. Such studies would connect business, information, engineering and analytics perspectives on digitalization and SC risks in order to bring the discussion further with the help of a conceptual framework for researching the relationships between digitalization and SC disruptions risks. Examples of the questions to be answered are, e.g., (1) what relations exist between big data analytics, Industry 4.0, additive manufacturing, advanced trace & tracking systems and SC disruption risks; (2) how digitalization can contribute to enhancing ripple effect control; and (3) what digital technology-based extensions can trigger the developments towards SC risk analytics.

At the proactive level, optimization and simulation models produce notable insights for managers and can be applied where the probability of disruption can be roughly estimated. On the one hand, big data analytics and advanced trace and tracking systems may help in predicting disruptions and providing more accurate data to build sophisticated disruption scenarios for resilient SC design analysis. Digital technologies open new problems for resilient SC design. For example, additive manufacturing changes SC designs whereby new resilient sourcing problems may arise. This area can further be enhanced using collaborative purchasing platforms.

At the reactive level and with regards to mitigation strategies and identifying disruption impact on finance and operational performance, digital technologies can be extensively used to obtain real-time information on the scope and scale of disruptions, their propagation in the SC and to simulate possible recovery strategies. In addition, at the reactive level, adaptation is necessary for achieving desired output performance by ensuring the possibility of changing SC plans and inventory policies. Adaptation processes in ripple effect control can be supported by feedback and adaptive control methods using decentralized agent techniques with the help of digital technologies. Visualizing these processes through virtual reality-supported simulation has not yet been done extensively to model the ripple effect in the SC. For this, simulation models, along with new digital technologies, can improve tools which are already used in developing SC agility and visibility in terms of disruption velocity.

3 RESILEANNESS AS A COMBINATION OF RESILIENT AND LEAN: LOW-CERTAINTY-NEED SUPPLY CHAINS

Uncertainty and risk predictions are commonly researched in studies of SC disruption management, mostly assuming known disruptive event or disruption scenario probability. The resulting resource allocation and costs have frequently resulted in expensive systems which help businesses cope with uncertainty. Without undermining the importance of further developing this common perspective, new approaches need to be developed that focus on the reduction of SC behavior dependence on environmental changes.

The unpredictability of the occurrence of disruption and its magnitude suggests that designing SCs with a low need for "certainty" may be as important, if not more so, than predetermined pre-disruption strategies. While the problem of disruption impact investigation with disruption probability estimations has attracted considerable research attention, some fundamental issues in this research stream need to be pointed out, such as fair probability estimation of rare events, consideration of only "known" events and the exclusion of "unknown" events, and the consideration of mainly the direct effects of disruptions in model outputs rather than disruption propagation chains and the resulting indirect effects (Mizgier et al. 2013, Macdonald et al. 2018). Such new perspectives in SC disruption management can be placed under the umbrella of low-certainty-need (LCN) SCs (Ivanov and Dolgui 2018). The ultimate objective of the LCN SCs is to develop the ability to operate according to planned performance regardless of environmental changes.

The LCN SC framework suggests approaching SC disruption risk and the ripple effect field from another perspective. Rather than opposing the efficiency and resilience, we suggest considering their mutual intersections to enhance each other based on synergetic effects in terms of SC *resileanness*.

Major costs of disruption management are seen in disruption prediction, protective redundancy, and reactive capabilities as a result of a higher need for certainty and the resulting higher redundancy and recovery efforts. As such, we suggest studying these areas from the perspective of efficiency and resilience complementarity.

Therefore, three key elements of the LCN SC framework can be identified as follows:

- Structural simplification and variety
- Process and resource utilization flexibility
- Efficient parametric redundancy.

Let us discuss the principles of implementing the LCN SC framework in practice. The ultimate objective of the LCN SC design is to develop the ability to operate according to planned performance regardless of environmental changes.

As such, the SC design from the position of resileanness (i.e., a combination of resilient and lean) possess two critical capabilities, i.e.,

- low need for uncertainty consideration in planning decisions and
- low need for recovery coordination efforts.

Structural variety, process flexibility, and parametrical redundancy ensure disruption-resistance and recovery resource allocation and allow for SC operation in a broad range of environmental states. This means that planning activities in the LCN SCs do not heavily rely on uncertainty prediction and proactive protection investments. Similarly, recovery coordination efforts are reduced to a minimum. Note that the LCN SC design does not necessarily imply higher costs, but rather seeks for an efficient combination of lean and resilient elements.

3.1. Structural variety and complexity reduction

Structural complexity reduction can be achieved by product line-based resilient SC segmentation with minimum intersections between the different lines, e.g., avoiding sourcing from the same supplier in the different lines. Such a composition results in a combination of lean SC design in individual product lines and resilient SC design. As such, disruption

propagation and the ripple effect can be reduced. A new research direction focusing on lean and resilient network structures can be seen in this area.
With regards to the structural variety, it can be recommended to continue using the consolidation effects subject to efficiency increases. A new research direction for identifying the risk exposure of consolidation nodes in SCs can be pointed out in this area. More specifically, resilient SC designs are expected to use consolidation effects at low-exposure (i.e., non-critical) network nodes. The latter aspect directly interrelates with the product line-based SC design. Therefore, a combination of structural variety and complexity reduction areas is the next new research avenue at the semantic level.

3.2. Process and resource utilization flexibility

Process and resource utilization *flexibility* means in a wider sense an establishment of universal, very flexible workstations such as those postulated in Industry 4.0 systems. Similar, the usage of universal materials can be considered with regards to recovery flexibility in the SC. Additive manufacturing technology can also positively influence product and process flexibility resulting in a combination of efficiency and resilience. The decentralized control principles in Industry 4.0 systems make it possible to diversify the risks with the help of manufacturing flexibility increases. New research directions can be seen with regards to the impact of the digitalization on the SC design resilience (Ivanov et al. 2019, Dubey et al. 2019a,b, Dolgui et al. 2019a,b). For example, Big Data analytics and advanced Trace &Tracking systems in general, and blockchain technology in particular, can help to trace the roots of disruptions, to observe disruption propagation (i.e., the ripple effect), to select short-term stabilization actions based on a clear understanding of what capacities and inventories are available (emergency planning), to develop a mid-term recovery policy, and to analyze the long-term performance impact of the ripple effect.

3.3. Parametric redundancy

Non-expensive parametric redundancy targets the efficient reservations of capacity, inventory, and lead time. More specifically, those reservations need to be considered not as a non-used redundancy, but rather for use in normal operation modes as well. Network redundancy optimization can be viewed as a new research topic in this area. Another aspect of parametric redundancy is its efficient allocation. A new research direction extending the existing value-stream mapping techniques towards the SC resilience can be considered. Efficient redundancy can be implemented by using additive manufacturing that helps to reduce the need for risk mitigation inventory and capacity reservations.

4 PROACTIVE PLANNING, NETWORK REDUNDANCY AND SITUATIONAL RECOVERY CONTROL

The research in ripple effect control needs to be united by three basic principles of system-cybernetic research. The *first* principle is the integrated modelling of resilient network structures. New principles and methods of SC structural dynamics control will be developed using a variety of methodologies for multi-criteria network synthesis and analysis. A particular focus will be directed towards the deployment of post-disruption management, and understanding which factors fit the particular dynamics the SC structures confront. The *second* principle is the proactive planning and network redundancy optimization. The given paradigm combines both SC robustness (i.e., the ability to absorb disturbances and continue execution with minimal impact on performance), monitoring (i.e., real-time disruption identification and data-driven re-planning preparation), and resilience (i.e., the ability to sustain and restore SC functionality using recovery and adaptation policies).
The *third* principle is the situational proactive control. A disruptive event, planning of the recovery control policy, and implementation of this policy are distributed in time and subject to SC structural and parametrical dynamics. In other words, both environment, SC structures and its operational parameters may change in the period between the planning of the recovery control policy and its implementation. As such, situational proactive control with a combined usage of simulation-optimization and analytics is needed to improve the transition processes from a disrupted to a restored SC state. This allows reducing investments in robustness and increasing resilience by obviating the transition process control problems. A combination of these three principles builds a framework of future decision support systems for SC disruption risk management which utilizes two major ideas, i.e., (i) low-certainty need SC designs and network redundancy optimization with an optimal combination of robustness and adaptation elements to ensure both efficient and resilient SCs and (ii) integrated SC ripple effect modeling with simulation, optimization, and analytics components to support situational forecasting, predictive simulation, prescriptive optimization, and adaptive learning.

5. DIGITAL TWIN AND RIPPLE EFFECT CONTROL: TOWARDS SUPPLY CHAIN RISK ANALYTICS

Analysis of current and future research trend in ripple effect allows formulating two important insights which lead the discussion further towards SC risk analytics.
Examples of SC and operations analytics applications include logistics and SC control with real-time data, inventory control, and management using sensing data, dynamic resource allocation in Industry 4.0 customized assembly systems, improving forecasting models using Big Data, machine learning techniques for process control, SC visibility and risk control, optimizing systems based on predictive information (e.g., predictive maintenance), combining optimization and machine learning algorithms, and simulation-based modeling and optimization for stochastic systems.
Success in SC competition will become more and more dependent on analytics algorithms in combination with optimization and simulation modelling. Initially intended for process automation, business analytics techniques now disrupt markets and business models and have a significant impact on SCM development. As such, new disruptive SC business

models will arise where SCs will be understood not as rigid physical systems with a fixed and static allocation of some processes to some firms. Instead, different physical firms will offer services of supply, manufacturing, logistics, and sales which will result in a dynamic allocation of processes and dynamic SC structures (Ivanov et al. 2018).

With the help of optimization and simulation approaches, current research generates new knowledge about the influence of disruption propagation on SC output performance considering disruption location, duration and propagation and recovery policies. New digital technologies create new challenges for the application of quantitative analysis techniques to SC ripple effect analysis and open new ways and problem statements for these applications.

The modelling stage is devoted to predictive simulation and prescriptive optimization. Disruption scenario simulation, SC design optimization, and recovery optimization belong to major decisions to be supported at this level. Structural dynamics control approach in combination with mathematical optimization can be used. Real-time control area contains supply flow real-time control, disruption identification, and real-time performance and recovery control. Feedback control can be applied in this domain with modifications.

It is commonly known that feedback control in socio-organizational differs from technical systems where the feedback can be implemented almost immediately. As such, the differences in the system states can be observed between the system state at the moment of starting to prepare the adjustment decisions on the basis of the feedback information and the system state at the moment of decision implementation. In other words, delayed feedbacks occur due to system inertia. The correction (adaptation) decisions need to be implemented at the object or system which is different from the object or system that has been considered for the reconfiguration decision planning. Finally, learning stage is comprised of risk mitigation learning, disruption recovery learning, and disruption pattern recognition. A combination of control algorithms and artificial intelligence can provide a number of new insights in the given area.

As such, a new generation of simulation and optimization models can be observed that extends the decision-support systems (DSS) towards decision analysis, modelling, control and learning systems (DAMCLS) in the form of digital SC twins. Combination of simulation, optimization and data analytics constitutes a full stack of technologies to create a digital supply chain twin – a model that always represents the state of the network in real-time. At each point of time, a digital twin represents the physical SC with the actual transportation, inventory, demand, and capacity data.

The DAMCLS system for SC risk analytics aims at proactive, resilient SC design in anticipation of disruptions and structural-parametrical adaptation in the case of disruptions. The decision-support system is based on a concept that combines simulation, optimization, and data analytics. The Simulation-Optimization part of the system is intended to provide proactive, resilient SC optimization and simulation of SC dynamic behavior in the event of disruptions or disruption scenarios.

In addition, this supports reactive, predictive simulation of disruption impacts on SC performance and of recovery policies which are subsequently optimized in the prescriptive manner using an analytical model. The data analytics part of the system is applied to disruption identification in real-time using process feedback data, e.g., from sensors and RFID. In addition, this aims at automated data input of disruption data into the reactive simulation model for recovery policy simulation and optimization. Finally, data analytics is used as data-driven learning system at the proactive stage, helping to generate adequate disruption scenarios for resilient SC design and planning.

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