Open access • Journal Article • DOI:10.1080/00207543.2018.1521025

Low-Certainty-Need (LCN) supply chains: a new perspective in managing disruption risks and resilience — Source link

Dmitry Ivanov, Alexandre Dolgui

Institutions: Berlin School of Economics and Law, Centre national de la recherche scientifique

Published on: 22 Jan 2019 - International Journal of Production Research (Taylor & Francis)

Topics: Supply chain risk management, Supply chain engineering and Supply chain

Low-Certainty-Need (LCN) supply chains: a new perspective in managing disruption risks and resilience

Dmitry Ivanov, Alexandre Dolgui

This is an Accepted Manuscript of an article published by Taylor & Francis in IJPR on Sept 14, 2018, available online: https://doi.org/10.1080/00207543.2018.1521025

Low-Certainty-Need (LCN) Supply Chains: A New Perspective in Managing Disruption Risks and Resilience

DMITRY IVANOV[1], ALEXANDRE DOLGUI[2]

[1] Berlin School of Economics and Law, Department of Business and Economics
10825 Berlin, Germany; Phone: +49 3085789155; email: divanov@hwr-berlin.de
[2] IMT Atlantique, LS2N, CNRS
La Chantrerie, 4, rue Alfred Kastler, 44300 Nantes, France
email: alexandre.dolgui@imt-atlantique.fr

**Corresponding author*
Prof. Dr Dmitry Ivanov
Berlin School of Economics and Law
Department of Business and Economics
Professor of Supply Chain Management
10825 Berlin, Germany
Phone: +49 3085789155;
email: divanov@hwr-berlin.de

Abstract

This study suggests a new approach to supply chain (SC) disruption risk management where SC behavior is less dependent on the certainty of our knowledge about the environment and its 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 disruption control strategies. In this setting, this study calls for the development of a new perspective in SC disruption management, i.e., low-certainty-need (LCN) SCs. A number of perspectives is derived in recent, relevant literature to identify the characteristics of the LCN framework and its management. Structural variety, process flexibility, and parametrical redundancy are identified as key LCN SC characteristics that ensure efficient disruption resistance as well as recovery resource allocation. Two efficiency capabilities of the LCN SC are shown, i.e., low need for uncertainty consideration in planning decisions and low need for recovery coordination efforts based on a combination of lean and resilient elements. The results allow the identification of an LCN SC framework, concepts and technologies for its implementation as well as missing themes and new research questions which contribute to a better understanding of SC disruption risks. Special focus is directed on the digital technology usage in the LCN framework implementation.

Keywords: supply chain design; supply chain risk management; supply chain resilience; supply chain dynamics; supply chain engineering; disruption; recovery; ripple effect; digital supply chain; robustness

1. Introduction

Supply chain (SC) design and planning seek to find a structural-process-parametrical form of a value-adding network and its operation in time subject to some goal criteria, e.g., costs minimization (Chopra and Meindl 2015, Ivanov et al. 2017a, Calleja et al. 2018). SC design is typically related to structural SC formation, and SC planning is concerned with process deployment. SC design and planning with disruption risk considerations (such as man-made and natural disasters or strikes) became extremely important in the last decade with the increase in complexity and the uncertainty of those networks.

Networking complexity in the SC frequently leads to disruption propagations through multiple stages: this is called the ripple effect (Liberatore et al. 2012, Ivanov et al. 2014a,b, Han and Shin 2016, Ivanov 2017, Akkermans and van Wassenhove 2018, Dunke et al. 2018, Scheibe and Blackhurst 2018, Dolgui et al. 2018). Uncertainty prediction and SC restoration or reconfiguration are two common research topics in SC disruption risk management that aim at mitigating the adverse effects of disruptions on SC financial and operational performance (Blackhurst et al. 2005, Tang 2006, Craighead et al. 2007, Handfield and McCormack 2008, Blackhurst et al. 2011, Gurnani et al. 2012, Sodhi et al. 2012, Tang et al. 2012, Habermann et al. 2015, Yildiz et al. 2016, Heckmann 2016, Khojasteh 2018, Ivanov 2018). The management efforts and the resulting resource allocations have usually been directed towards disruption prediction, protective redundancy, and reactive capabilities.

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 (Klibi and Martel 2012, Sodhi and Tang 2012, Ivanov and Sokolov 2013, Fahimnia et al. 2015, Ho et al. 2015, Snyder et al. 2016, Chen et al. 2017, Jain et al. 2017, Behzadi et al. 2017, 2018, Dolgui et al. 2018, He et al. 2018, Macdonald et al. 2018, Song et al. 2018, Ribeiro and Barbosa-Povoa 2018, Ghavamifar et al. 2018).

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, Han and Shin 2016, Chen et al. 2017). Robustness is typically guaranteed by some redundancy such as structural diversification, flexible response options, and system adaptation condition improvement. At the same time, we may distinguish between *being safe* and *performing safely* (Haimes 2009, Park et al. 2013, Aven 2017). In contrast to robustness 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 (Aven 2017). SC resilience encompasses both proactive and reactive stages (Bhamra et al. 2011, Jüttner and Maklan 2011, Spiegler et al. 2012, Pettit et al. 2013, Brandon-Jones et al. 2014, Ambulkar et al. 2015, Tukamuhabwa et al. 2015, Chowdhury and Quaddus 2017, Yu and Yang 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 (Sheffi 2005, Tomlin 2006, Melnyk et al. 2014, Ivanov et al. 2016, 2018, Rezapour et al. 2017, Ivanov and Rozhkov 2017, Geng and Xiao 2017, Ivanov 2018).

Two observations from literature motivated this study. First, both robust and resilient SC designs frequently result in expensive systems to cope with uncertainty. In addition, the concepts of efficiency and resilience are rather considered in contradictory settings with direct assumptions of efficiency reduction with increases in resilience or *vice versa*. Uncertainty prediction and SC restoration or reconfiguration processes are mostly seen as major SC resilience drivers, whereby the costs of resilience negatively influence SC efficiency. To the best of our knowledge, there is no published research that tries to develop resilient *and* efficient SC design or control models.

Second, the literature differs regarding probability estimations and risk assessments of disruptions or the consequences of disruptions. While the problem of disruption impact investigation with disruption probability estimations has attracted considerable research attention (Chen et al. 2011, Zobel and Khansa 2014, Torabi et al. 2015, Sawik 2017, Pavlov et al. 2018), 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 effect. Another approach focuses on the recovery stage of SC resilience; this focus is the result of the unpredictability of the kind of events can occur, disruption magnitude, and the dynamics confronted (Lim et al. 2013, Simchi-Levi et al. 2015, Ivanov et al. 2017c). This is especially important in complex systems where multiple and frequently unknown effects may result following the structural dynamics (Ivanov et al. 2010, Aven 2017, Mizgier 2017, Macdonald et al. 2018).

This paper seeks to bring the discussion forward by carefully elaborating on the two issues described above and providing some ideas and implementation guidance on how to think in relation to these challenges. The purpose of the present study is to contribute to existing works by arguing that, rather than efficiency and resilience opposing each other, the consideration of these perspectives can be done within an integrated framework to enable SCs with lower requirements on certainty at both the proactive and reactive stages. As such, this study calls for the development of a new perspective in SC disruption management, i.e., low-certainty-need (LCN) SCs. The LCN SC concept can be considered as an analogy to the level strategy in Sales&Operations Planning that suggests maintaining a stable production system behavior as opposite to the chase strategy that continuously changes the system behavior according to changes in the system environment. The objectives of developing the LCN SC framework are to obtain insights on

- how *robust* and *resilient* SC design and planning can be integrated with the principles of *efficiency*,
- how to design and implement robust and resilient SC focusing on the SC's ability to efficiently operate *regardless of environmental changes*,
- how to reduce the re-planning efforts for disruption recovery with the help of efficient *proactive* robustness and recovery.

With this in mind and although this research investigates the disruption management process from the LCN SC perspective, our investigation does not neglect the importance of disruption probability estimation-based studies.

The rest of this study is organized as follows. The literature review is presented in Section 2. Section 3 develops the LCN SC framework. Practical implementation and future research directions are featured in Section 4. Section 5 concludes the paper by summarizing major insights and outlining limitations and future research needs.

2. Literature review

The literature review in sub-sections 2.1-2.3 is organized according to three levels, i.e., the semantic level, the process level, and the control level. In each of these sub-sections, a further classification in proactive and reactive studies is undertaken. A literature analysis scheme used with regards to this classification is shown in Appendix 1. Moreover, we point out the impact of the research results presented on efficiency and resilience as well as consider the methodologies used. All this allows us to build a framework from the existing literature on resilient SC design in Section 3 that will be used to develop the LCN SC framework.

2.1. Semantic level: Structural properties, complexity role, and critical nodes

2.1.1. Research focus

Disruptions and the resulting ripple effect cause SC structural changes, also referred to as SC structural dynamics (Ivanov et al. 2010, Ivanov 2018). Structural SC properties have been recognized to have a crucial impact on the ripple effect and SC robustness and resilience (Xia et al. 2004, Tomlin 2006, Nair and Vidal 2011, Hu et al. 2013, Basole and Belami 2014, Ivanov et al. 2014a,b, Ambulkar et al. 2015, Bode and Wagner 2015, Kim et al. 2015, Gunasekaran et al. 2015, Kamalahmadi and Mellat-Parast 2016, Hand and Shin 2016, Sokolov et al. 2016, Tang et al. 2016, Chen et al. 2017, Jain et al. 2018, Scheibe and Blackhurst 2018, Pavlov et al. 2018, Ojha et al. 2018).

A body of literature has been established that examines the impacts of different structural variations on SC performance for various risk attitudes in a decision maker, ranging from risk neutral to risk averse (Ho et al. 2015, Rangel et al. 2015, Yang and Babich 2015, Snyder et al. 2016, Ivanov et al. 2017c, Kumar et al. 2017, Sawik 2017, Reyes Levalle and Nof 2017, Yoon et al. 2018a, ~~Carbonara and Pellegrino 2018,~~ Namdar et al. 2018).

This literature at the structural level targets semantic network analysis in order to identify underlying interdependencies between network graph forms and SC robustness, flexibility, adaptability, and resilience (Basole and Belami 2014, Zobel 2014, Kim et al. 2015, Ivanov 2017, Giannoccaro et al. 2017, Ivanov et al. 2017a,b, Dolgui et al. 2018).

Likewise, a linkage of SC complexity and resilience can be observed in literature (Nair and Vidal 2011, Bode and Wagner 2015, Shukla and Kiridena 2016, Scheibe and Blackhurts 2017, Levner and Ptuskin 2017, Birkie et al. 2017, Samani and Hosseini-Motlagh 2018). Blackhurts et al. (2005), Ho et al. (2015), Jain et al. (2017), Ivanov et al. (2017a,b) underlined that global sourcing, product individualization, and cross-channel logistics strategies increase SC complexity. Scheibe and Blackhurst (2018) identified SC structure as one of three major drivers of disruption propagations in the SC.

The literature analysis shows that complex networks become more vulnerable to severe disruptions which change the SC structures and are involved with SC structural dynamics (Ivanov et al. 2010, Ivanov and Sokolov 2010, Mistree et al. 2017, Ivanov 2018). Moreover, the ripple effect in the SC depends on structural network composition and complexity (Hand and Shin 2016, Sokolov et al. 2016, Ivanov 2017a,b, Levner and Ptuskin 2017, Pavlov et al. 2018).

2.1.2 Structural properties: proactive stage

Chopra and Sodhi (2014) emphasized the impact of SC *centralization and decentralization* on SC resilience and disruption risk management. Their results call for decreases in resource concentration and SC segmentation in terms of volume, product variety, and demand uncertainty. Another finding of this study favors the localization of SC designs, which has a positive correlation to disruption risk propagation. The authors also provided evidence on the costs of decentralized and diversified SCs as opposed to efficient SC designs which are characterized by centralization, higher resource capacity utilization, globalization, and leanness. Basole and Bellamy (2014) focused on the identification of "healthy nodes" in the SC based on the level of risk diffusion, quantified as the number of functioning nodes at time t relative to the size of the network. Bode and Wagner (2015) revealed empirical interrelations between upstream SC complexity and the frequency of SC disruptions. They saw major reasons for such interrelations in the SC structural design.

Similar results have been gained by Kim et al. (2015). Different network structures and disruption impacts have been analyzed. The results confirmed a correlation between SC structural composition and resilience. Giannacaro et al. (2017) investigated the relationship between the scope of control (i.e., how much of its supply network a buying firm should control) and SC performance using a complex adaptive system approach. The results indicate that complexity negatively affects SC performance, with a performance decrease depending on the scope of control. Based on these findings, different control strategies to mitigate the negative influence of complexity are formulated. Adenso-Dias et al. (2018) showed that flow complexity, measured as the number of potential transportation links between SC nodes, is the most influential factor affecting SC robustness in terms of the service level that can be maintained after disruptions. Being useful and elegant in their computational simplicity, most of the works reviewed utilize simple additive or multiplicative approaches and topological indicators that do not allow for disruption propagation analysis and the capture of the resulting network interdependencies. Moreover, direct application of reliability theory methods to SC resilience analysis needs to be proofed in each particular case, since in general SC systems are different from technical systems. More specifically, time lags between disruption identification and recovery policy activation (e.g., due to time needed to coordinate with the supplier) and between disruption and performance impact (e.g., due to inventory buffers) need to be considered (Ivanov et al. 2017b).

Mizgier et al. (2013, 2015) and Mizgier (2017) as well as Ivanov (2017a) and Ivanov and Rozhkov (2018) used financial analysis and discrete-event simulation, respectively, and revealed that the model outputs in terms of performance impact of SC disruption cannot be completely explained by direct effect and should rather be considered in terms of disruption propagations and the resulting chains of indirect effects. This finding was further explained in the study by Chen et al. (2017) and Macdonald et al. (2018) that demonstrated the impact of indirect effects and disruption propagations on SC performance using the Bayesian method and discrete-event simulation, respectively. The findings of works in this area show that SC robustness and resilience should not merely be based on a straightforward disruption magnitude analysis, but rather seek trajectories of how different disruption scenarios influence the severity in network degradation (Cats et al. 2017, Pavlov et al. 2018). To this end, the direct effect of the weakest link on SC performance does not always represent the worst-case scenario, and it must be considered a multiple dimension which is subject to the entire range of disruption propagation and the resulting indirect effects of the chain of capacity reductions.

Another perspective is taken in the research on reliable facility location planning. Beginning with the study by Snyder and Daskin (2005) and continued by Lim et al. (2010), Peng et al. (2011), and Li et al. (2013), those mixed-integer optimization models develop according to a scenario-based approach with probabilities of facility disruption. The objective is to determine which SC designs are considered to be reliable with regards to some robustness or reliability estimations such as p-robustness criterion (i.e., cost bounds in disruption scenarios) in the study by Peng et al. (2011). Lim et al. (2010) and Li et al. (2013) highlighted issues of *facility fortification* to reduce the negative impacts of disruption risks. Lim et al. (2010) designed a mixed-integer programing model with a fully reliable backup supplier. The associated recovery costs are integrated into the objective function. Li et al. (2013) furthered this model, applying limitations to the fortification budget.

2.1.3. Structural robustness and recoverability: reactive stage

Ivanov et al. (2010) developed a SC structural dynamics control model that has been frequently used for multi-structural SC design analysis under uncertain conditions. Raj et al. (2015) applied a survival model to simulate the recovery time in the SC. Using the event of failure as the model input and the recovery time as the model output, they proposed to measure SC resilience using recovery time. Sokolov et al. (2016) applied the AHP method to analyze the dependencies of different SC structures in terms of their recoverability. They estimated network connectivity, reachability, complexity, and centralization, and used these indicators to analyze the performance impact of the ripple effect in a distribution network. Macdonald et al. (2018) considered structure, centrality, and density of the network as the indicators which allow assessment of the amplification or dampening of shocks passing through the SC.

In *random networks*, Han and Shin (2016) studied disruption propagation in the SC and evaluated SC structural robustness. Lin at al. (2017) assessed SC reliability as a probability of meeting customer demand with considerations of alternative routes in the SC design. Reliability was assessed by the number of minimal paths. Pavlov et al. (2018) developed a hybrid fuzzy-probabilistic approach to SC resilience estimation with structural dynamics and ripple effect consideration. The genome method was applied with the objective of including the structural properties of SC design into the resilience assessment. The same study posited that the SC design resilience index that can be used as a method of comparing different SC designs regarding resilience both to disruption propagation and with recovery consideration. Moreover, the developed approach allows the identification of groups of critical suppliers whose failure interrupts SC operation.

Finally, *entropy-based* studies play an important role at the semantic analyis level. Harremoës and Topsøe (2001) studied SC vulnerability using maximum entropy and a real-world healthcare SC example. Allesina et al. (2010) developed eight indexes based on entropy to measure the level of SC complexity by mapping the exchanges of goods between the different actors in the network. The impact of possible modifications of the SC structure can be evaluated using these tools, providing an evaluation of the different structural dynamics scenarios. Arkhipov and Ivanov (2011) and Ivanov and Arkhipov (2011) applied the entropy model to the analysis of SC adaptation potential. They also developed modifications in regard to real-scale SC structures. Levner and Ptuskin (2017) addressed ripple effect analysis using entropy measures from the environmental risk perspective.

Insights: The semantic network analysis literature pertains to the dependencies of SC robustness and resilience on the structural complexity that increases uncertainty and disruption risk propagation. The quantitative methodologies used mostly include mathematical optimization, simulation, graph theory, game theory, control theory, complexity theory, financial analysis, and reliability theory. The major findings in this research stream pose the impact of different structural SC designs, e.g., in terms of the critical nodes on disruption-based SC structural and performance dynamics. The issues of segmentation, diversification, backup suppliers, facility fortification, globalization, and localization are considered important managerial levers to increase SC resilience at the proactive and reactive stages. In summary, <u>structural variety and recoverability</u> can be considered a major SC resilience driver, as identified at the semantic structural analysis level.

2.2. Process level

2.2.1 Research focus

Flexibility has been mostly analyzed at the process level (Tang and Tomlin 2008, Ivanov et al. 2014a, Simchi-Levi et al. 2015, Dolgui et al. 2018, Ivanov 2018). The literature mostly focuses on product and process flexibility to ensure SC robustness and resilience. The respective ripple effect control framework has been elaborated by Dolgui et al. (2018). The literature recognizes flexibility as a major driver of resilient SCs. The papers in this research stream investigate the use of flexible production and sourcing processes to achieve SC robustness and resilience under disruptions. The coping strategies, the authors indicate, consider dual and multiple sourcing whereby the focus of analysis includes a tremendous variety of proactive and reactive measures such as backup supplier contracts, pricing policy adjustment, advanced, spot and contingency purchasing, risk mitigation inventory, capacity reservations, product flexibility and postponement, and collaboration and visibility.

2.2.2 Product and process redundancy: proactive stage

Kleindorfer and Saad (2005) considered sourcing flexibility, inventory, and capacity excessiveness as major drivers of resilience in the SC. Companies invest in structural process redundancy in terms of sourcing flexibility (e.g., Toyota extends its SC subject to multiple-sourcing and building new facilities on the supply side). A mature body of literature in the research stream on using dual/multiple sourcing has evolved over the last decade (Babich et al. 2007, Yang et al. 2009, 2012, Yu et al. 2009, Bakshi and Kleindorfer 2009, Liberatore et al. 2012, Kim and Tomlin 2013, Hu and Kostamis 2015, Zhu 2015, Tsai 2016, Ivanov 2016, 2017c, Bakal et al. 2017, Ivanov 2017a,b, Sawik 2016, Ang et al. 2017, Yin et al. 2017, Schmitt et al. 2017, Ulutas et al. 2017, Yin and Wang 2018, Yoon et al. 2018b).

For example, Ravindran et al. (2012) developed multi-criteria supplier selection model. They considered price, lead time, disruption risk, and quality risk as four conflicting objectives. Goal programing was used to solve the multi-objective optimization problem. Rafiei et al. (2013) considered a backup supplier with reserved capacity and a backup transshipment node. This redundancy is used to satisfy demand at a higher price in the case of a disruption at the primary supplier. Ivanov (2017b) showed that single sourcing enhances the ripple effect and a reduction in storage facilities in the SC downstream of a disruption-risky facility causes the ripple effect. The role of backup suppliers in SC resilience is highlighted in this study. Sawik (2016, 2017) applied stochastic optimization methodology and developed a portfolio approach to SC disruption management. Like Lim et al. (2010) and Peng et al. (2011), Sawik's studies used the probabilities of the disruption scenarios instead of standard probability distributions which have a very restrictive application to low-frequency disruptive events. Along with the study by Yoon et al. (2018a), Sawik's studies suggested models that integrate supplier selection and risk mitigation strategy selection. An alternative approach was taken in the study by Yu et al. (2017) that applies robust stochastic optimization to SC design. Based on the regret minimization method, their findings allow the balancing of the conservativeness of a pure robust optimization model and the optimism of risk-neutrality.

Another research stream focuses on the contract-based SC *coordination* with supplier or market disruption considerations. Game-theoretic studies dominate this research field (Hu and

Kostamis 2015, Tsai 2016, Li et al. 2017). Gupta et al. (2015) analyzed the impact of contingent sourcing strategy under competition and in the presence of a possible supply disruption. The results indicate that supply disruption and procurement times jointly impact the firms' buying decisions. The findings in He et al. (2016) showed that reliability thresholds play a critical role in buyer procurement strategy choices, which are related to sales price, underage cost, and differentials in unit procurement cost. They explored the effects of reliability levels and costs on equilibrium prices, expected profits, and equilibrium strategy profiles. According to the results presented, the competing buyers chose the same strategy, whether an optimal allocation strategy with single sourcing or an emergency procurement strategy with dual sourcing. Ang et al. (2017) found that the manufacturer's optimal strategy depends on the degree of overlap in the SC. If the Tier 1 suppliers share Tier 2 suppliers, the manufacturer relies less on direct mitigation, i.e., multi-sourcing in Tier 1 and more on indirect mitigation, i.e., inducing Tier 1 suppliers to mitigate disruption risk.

Companies also implement product and process redundancy. With regards to *product flexibility*, postponement plays an important role in increasing SC flexibility. ~~With regards to both product flexibility and disruption risks,~~ Carbonara and Pellegrino (2017) analysed flexibility strategies to mitigate SC disruption risks. This research is related to that of product substitution under disruptions, mostly with considerations of pricing decisions using game theoretic modeling (Lu et al., 2011, Li et al. 2017, Kumar et al. 2018). Simchi-Levi et al. (2018) provide evidence that process flexibility and inventory should be considered as important drivers of SC robustness.

2.2.3. Product and process flexibility: reactive stage

One of the major new drivers in SC flexibility research is its embedding into the disruption risk management framework (Dolgui et al. 2018, Ivanov 2018). Flexibility considers indirect usage of the structure and process redundancy in terms of changing the system behavior by reallocating SC inventories, capacities, and sourcing facilities. Stevenson and Spring (2007) defined robust network flexibility as the range of events with which the existing SC structure is able to cope, and the reconfiguration of flexibility regarding modification (adaptability) of the SC. Yadav et al. (2011) analyzed SC flexibility in the context of robustness with a focus on flexible product families and diversification. Seifert and Langenberg (2011) analyzed SC flexibility and adaptability in a joint framework with product decisions.

A discrete-event AnyLogic simulation model by Ivanov and Rozhkov (2017) considered capacity disruptions at a factory for a real-life example of a retail SC with product perishability considerations. Their results revealed that production-ordering policies during the disruption period impact the post-disruption SC's operational and financial performance. Flexible contingent production-ordering coordination is therefore positive for inventory dynamics stabilization, improvement in on-time delivery, and variation reduction in customer service level. The issues of process expediting are highlighted in the study by Schmitt et al. (2017) at the recovery stage. The results highlight the negative effects of process expediting as a recovery policy with regards to SC performance.

Insights: Flexibility is the central theme of the research conducted at the process level referring the ability of production, sourcing, and transportation systems in the SC to change (adapt) in dynamic environments. The methodologies used include mathematical optimization, discrete-event simulation, game theory, and real options. Backup and dual sourcing, postponement, product substitution, production capacity flexibility, and coordination have been identified as major elements of the contingency processes and SC resilience drivers to be addressed at the process management level. Increasing SC resilience is considered in the flexibility framework in light of some process redundancy (e.g., a more expensive backup source) as opposed to process leanness.

2.3. Control level

2.3.1 Research focus

The research focus at the control level is directed at process parameters such as inventory, capacity utilization, and lead time. High inventory, capacity reservations, and lead time reserves may help to increase SC resilience, but might negatively affect efficiency.

2.3.2 Parametric redundancy: proactive stage

Using system dynamics, Wilson (2007) showed how fulfilment rate and inventory fluctuations are impacted by the ripple effect during transportation disruptions in multi-stage SCs. The results of the study point to transportation disruptions between the Tier-1 supplier and the warehouse as having the highest performance impact. Using discrete-event simulation, Schmitt and Singh (2012) analyzed the role of inventory reserves in SC performance under disruptions. They found that increases in raw material and finished goods inventories as a prevention measure against disruptions are considerably larger than those required based on stochastic demand, and, second, "upstream disruptions in the SC may not be felt as quickly as downstream disruptions, but their impact can be amplified, outlasting the disruptions themselves." Dependence on the employment efficiency of backup mitigation methods also became evident through this study.

Shao and Dong (2012) studied an assemble-to-order system with a backup source to offer on-time delivery and a compensation policy to compensate customers for waiting in each period during the disruption. According to their results, a backup sourcing strategy is preferred at the beginning of the supply disruption, while the compensation strategy is preferred as time elapses. The dynamic mixed strategy with customer choices is superior to the pure backup sourcing strategy. The manufacturer's choice of reactive strategies is determined by backup costs and customer sensitivity. Incentive mechanisms to motivate a supplier's investment in capacity restoration have been analyzed by Hu et al. (2013). They considered pre-disruption and post-disruption stages and found that with buyer offer incentives, both the buyer and the supplier (weakly) prefer the pre-disruption commitment over the post-disruption recovery. Recovery capacity investment has been studied by Kim and Tomlin (2013). They showed that firms in a decentralized setting overinvest in capacity, resulting in higher system availability, but at a higher cost. If both investments can be made, the firms typically underinvest in failure prevention and overinvest in recovery capacity.

The results of a discrete-event simulation study by Ivanov (2017a) showed that the ripple effect enhances the performance impact of disruptions. Upstream disruptions are more likely to result in ripple effects in the case of single source policy. A safety stock increase is recommended at the facilities downstream of disruption-risky SC elements. Higher inventory levels in the downstream SC dampen ripple effect propagation towards the customers. At the same time, a safety stock increase at disruption-risky facilities should be considered carefully, since if these facilities are not able to perform outbound operations (e.g. fire or strike) the increased safety stock is not useful for dampening the ripple effect.

Rezepour et al. (2017) found out that the best alternative in the case of unreliable suppliers is downstream "emergency stock." Yin and Wang (2018) showed that an advance purchase strategy is recommendable if the disruption probability is high, while contingency purchase strategy benefits the firm more under a low disruption probability. Under an intermediate disruption probability, the firm should choose reservation strategy only if the reservation fee is sufficiently low. Another finding of their study is that the advance purchase and the reservation strategy should be adopted more widely when the dedicated supplier guarantees a relatively high yield rate after disruption. A SC simulation model was developed by Macdonald et al. (2018) that distinguishes shock nature (i.e., disruption interarrival time), ecosystem (i.e., network connectivity), and investment levels (i.e., buffer stock). This study brings the redundancy analysis level into correspondence with the network analysis level.

2.3.3. Parametric feedback control: recovery stage

Control theory methodologies have been applied to SC disruption analysis. Ivanov et al. (2013, 2014b, 2016, 2017b) included speed and time of recovery into consideration and developed a hybrid control-based model blended with linear programing in order to analyze different recovery policies with regards to performance impact. They showed the impact of transportation and warehouse capacity on SC service levels and costs.

The studies by Spiegler et al. (2016) as well as by Wang and Disney (2012) and Wang et al. (2015) underlined that non-negativity nonlinearity can cause limit cycles, which are oscillations intrinsic to nonlinear production and inventory control system itself and not imposed by demand. Another finding is that nonlinearity in the shipment system has no impact on the order rate and work-in-process inventory. Nonlinearity in the shipment system is frequency-dependent and not only high demand levels, but also too medium-low frequency demands possibly cause higher backlogs. Spiegler et al. (2016) applied nonlinear control theory to investigate the underlying dynamics and resilience of a grocery SC. The authors presented a control loop for the distribution center replenishment system.

Insights: Parametric <u>*redundancy*</u> *is a central research category at the control level. Insufficient redundancy is risky. Redundancy is costly. This trade-off presents a central issue in the research at the parametric redundancy control level. High inventory, capacity reservations, and lead time reserves may help in increasing SC resilience, but they negatively influence SC efficiency. The methodologies used in this research area include mathematical optimization, discrete-event simulation, system dynamics, and control theory.*

2.4. Research gap analysis

In Table 1, we summarize the research gaps identified at semantic, process, and control levels.

Table 1. Research gaps at semantic, process, and control levels

Analysis levels	**Research gaps**
Semantic level	*The semantic network analysis pertains to the dependencies of SC robustness and resilience on structural network properties. Which structural SC designs, e.g., in terms of the critical nodes, can help to increase SC robustness and reduce the need for disruption-driven process changes? How can segmentation, diversification, backup suppliers, facility fortification, globalization, and localization be applied to increase SC resilience whilst remaining lean and efficient? Which SC design patterns can provide quicker and more efficient recoverability?*
Process level	*Backup and dual sourcing, postponement, product substitution, production capacity flexibility, and coordination are major elements of contingency processes and drivers of SC resilience. How can process redundancy be allocated to increase SC robustness and reduce the need for*

	disruption-driven process changes? How can process redundancy (e.g., a backup source) be applied whilst remaining lean and efficient? Which reactive process flexibility policies can help in efficient SC recovery?
Control level	*High inventory, capacity reservations, and lead time reserves may help in increasing SC resilience, but they negatively influence SC efficiency. How can parametric redundancy be applied to increase SC robustness and resilience whilst remaining lean and efficient? Which reactive control policies can help in efficient SC recovery?*

As shown in Table 1, a number of research gaps can be identified that motivate the development of the LCN SC framework. First, structural SC design patterns need to be identified that allow for both efficient robustness and recoverability. Second, process flexibility policies need to analysed which enable the reduction of disruption-driven process changes and efficient SC recovery. Finally, at the control level, the efficient usage of parametric redundancy and the development of reactive control policies are also research gaps that drive the pursuit to establish the LCN SC framework.

3. Low-certainty-need (LCN) supply chain framework

3.1 The generalization of literature analysis

The LCN SC framework development is based on the following methodology. The literature review (cf. Section 2) has been developed on the basis of a structured approach. The database SCOPUS and the expert knowledge of the author have been used to identify the relevant papers subject to keywords “supply chain” <and> (“resilience” or “robustness” or “redundancy” or “disruption” or “recovery” or “adaptation”). The narrowed list of papers have been studied extensively. An additional textual analysis has been performed regarding the keywords “backup,” “flexibility,” “reservation,” “mitigation,” “dual,” “complexity,” and “contingency.” Semantic (structural), process, and control (parametric) perspectives of disruption risk and resilience management have been classified. In this setting, resilient frameworks and efficient SC design techniques have been considered. The combination of this analysis and the classification into structural, process, and control levels was used to develop the LCN SC framework and derive properties that SCs should possess being robust, resilient, and efficient. This analysis culminates with the LCN SC framework that can be utilized to establish both efficient and resilient SCs. The LCN framework is also used further in the paper to develop a nomological framework for research propositions for future research.

The generalization of analysis considered in Sect. 2 allows formation of a framework on resilient SC design and planning as shown in Fig. 1.

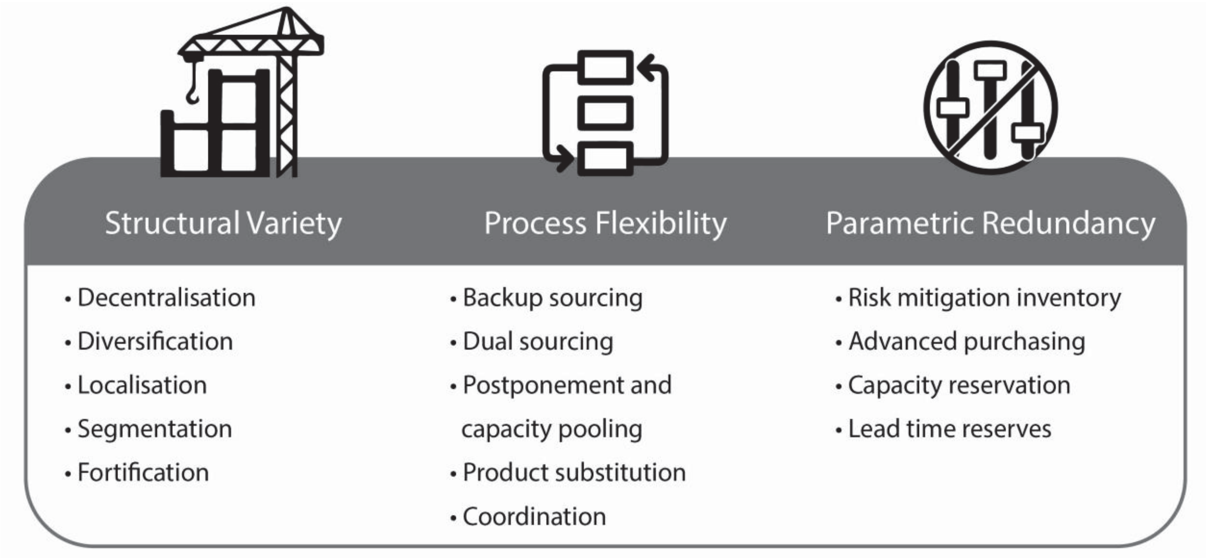


Fig. 1. Literature framework on resilient SC design and planning

Notwithstanding the diversity of knowledge and findings about resilient SC design and planning, a generalization of literature allows identification of structural variety, process flexibility, and parametrical redundancy as key characteristics that ensure disruption-resistance and recovery resource allocation and allow for SC operation in a broad range of environmental states.

While the process of SC disruption management has attracted considerable research attention, much of it has had roots in disruption probability. At the same time, a fair probability estimation of rare events is a complicated problem and even small errors in those estimations may significantly impact the modeling results (Chan and Kroese 2011). The unpredictability of disruption appearance and its magnitude suggests that designing SCs with a low need for "certainty" may be as important, if not more so, than pre-determined pre-disruption strategies. This study seeks to identify the perspectives of the LCN framework, and its management.

3.2 Low-certainty-need (LCN) supply chain framework

SC risk classifications in Chopra and Sodhi (2004), Tang and Musa (2011), Sodhi et al. (2012), Quang and Hara (2017) and Dolgui et al. (2018) allow the distinguishing of external risk such as fire accidents, natural catastrophes, and strikes, demand risk, supply risk, and time risk referring to delays in SC processes. Considering these risks and the results depicted in Fig. 1, Table 2 summarizes SC design efficiency, sources of uncertainty, resilience measures, and costs of certainty.

Table 2 Supply chain design and costs of resilience

Analysis levels	**Supply chain design**		**Costs of resilience**	
	Efficient supply chain	Resilient supply chain	Sources of uncertainty	Costs of resilience
Structural level	Centralization Globalization	Decentraliation Diversification Localization Segmentation Fortification	External risks	Complexity costs
Process level	Standardization Single sourcing	Backup/dual sourcing Postponement Capacity pooling Product substitution Coordination	Demand risks Supply risks	Flexibility costs
Control level	Inventory reduction Leanness Capacity utilization	Risk mitigation inventory Lead time reserves Capacity redundancy	Supply risks Time risks	Redundancy costs

Following the classification of efficient SCs in (Fischer 1997), Table 3 extends it and depicts major differences between efficient and resilient SC designs.

Table 3 Efficient and resilient supply chain design (extended on the basis of Fischer 1997)

Criteria	**Efficient Supply Chains**	**Resilient supply chain**
Primary Goal	Supply demand at the lowest cost	Ensure demand fulfillment in the presence of disruptions
Network organization	Centralized, global	Decentralization, diversification, localization, segmentation, fortification
Product design strategy	Standardization, maximize performance at minimum product cost	Postponement to ensure product flexibility, product substitution, capacity pooling
Pricing strategy	Lower margins because price is a prime customer driver	Higher prices caused by the costs of resilience
Manufacturing strategy	Lower costs through high utilization	Capacity reservations
Inventory strategy	Minimize inventory to lower cost	Risk mitigation inventory
Lead time strategy	Reduce, but not at the expense of costs	Lead time reservations
Sourcing strategy	Select suppliers based on cost and quality; single sourcing	Supplier risk exposure analysis; backup suppliers and dual sourcing

It can be observed in Tables 2 and 3 that the concepts of efficiency and resilience are rather considered in contradictory settings with direct assumptions of efficiency reduction with resilience increases or *vice versa*. 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 (Fig. 2).

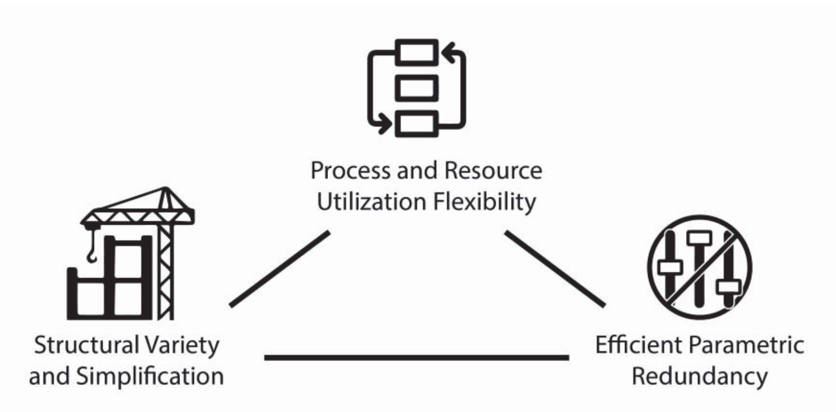


Fig. 2. Low-certainty-need supply chain framework

According to Fig. 1 and Tables 1 and 2, structural complexity, process inflexibility and non-flexible usage of resources and insufficient parametric redundancy increase uncertainty and disruption risk propagation in the SC. Therefore, three key elements of the LCN SC framework can be identified as follows (cf. Fig. 2):

- 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 and the resulting future research avenue needs in Section 4.

4. Practical implementation and future research avenues

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 LCN SC design 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.

4.1. 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. In particular, a supplier failure would affect only the product line that works with that supplier, and not the whole network due to the absence of intersections between the SCs in different product lines. 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. Moreover, new SC concepts driven by cyber-physical solutions can help to increase the SC robustness through faster and more reliable recognition of the potential external and internal disruptions and disturbances, and through the minimization or avoidance of their negative consequences (Monostori 2018, Ivanov et al. 2018).

4.2. Process and resource utilization flexibility

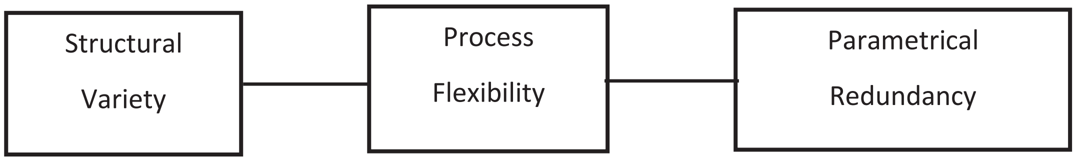
Process and resource utilization *flexibility* means in a wider sense an establishment of universal, very flexible workstations such as those postulated in Industry 4.0 systems. Similar, the usage of universal materials can be considered with regards to recovery flexibility in the SC. Additive manufacturing technology can also positively influence product and process flexibility resulting in a combination of efficiency and resilience. Additive manufacturing can reduce the need for backup contingency suppliers. 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. 2018). 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. Additive manufacturing has the potential to reduce disruption propagation in the SC since the number of SC layers and the resulting complexity would be reduced.

4.3. Non-expensive 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. Finally, new material classification schemes need to be developed subject to material criticality and risk exposure in terms of the efficient and resilience SC design.

4.4. Decision-support system for LCN supply chains

Finally, we integrate the fragmented perspectives on design, implementation, and future research in LCN SC in a preliminary nomological framework that can be used to develop a decision-support system for LCN SCs (Fig. 3).



Associated Research Propositions:

1. Decentralization increases SC resilience. Using product line-oriented SC segmentation, efficient decentralization can be implemented.

2. Localization increases SC resilience. Using new digital and smart operations technology such as additive manufacturing, efficient localization can be implemented.

3. Diversification increases SC resilience. New digital SC technologies such Industry 4.0 provide potential to implement an efficient diversification.

4. Backup/dual sourcing has a positive effect on SC resilience. Efficiency decreases as compared to single sourcing might be compensated by optimizing pricing and contracting.

5. Postponement and capacity pooling have a positive association with SC resilience. Using new digital and smart operations technology such as additive manufacturing, efficient postponement can be implemented.

6. Product substitution is an effective recovery policy that increases SC resilience. Pricing and contracting optimization allows implementing product substitution at reasonable costs.

7. Risk mitigation inventory increases resilience. The resulting efficiency decreases might be compensated by comprehensive material and supplier classifications in terms of risk exposure. Efficient allocation of risk mitigation inventory is another point of investigation

8. Capacity reservations, like risk mitigation inventory, create some "cushion" against the disruptions and are positively associated with resilience. Technology flexibility is the way to transit from pure reservations to flexible capacity usage in both normal and disrupted modes and to increase efficiency.

9. SC resilience has a positive association with time-to-recover. Lead time reservations allow an increase in SC resilience. Efficiency analysis with regards to lead time extensions is a new and still unexplored topic.

Fig. 3. Nomological framework of the low-certainty-need SCs

The decision support system for LCN SCs will 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.

The propositions developed in Fig. 3, as well as the relationships among the framework's conceptual constructs can be refined and tested in future studies, e.g., using comparative simulation experiments with consideration of other SC disruption risk approaches. The ever-increasing role of SC risk analytics need to be named as a promising way to further study the dependencies described in Fig. 3. For example, Resilience360 analytics tool developed at DHL (DHL2018) allows comprehensive disruption risk management by mapping end-to-end SC, building risk profiles and identifying critical hotspots in order to initiate mitigation activities and alert in near-real time mode on incidents that could disrupt the SC.

5. Conclusion

Uncertainty and risk predictions are commonly researched in supply chain (SC) disruption management, mostly assuming known disruptive event or disruption scenario probability. The resulting resource allocations have frequently lead to resilient but expensive systems which help businesses cope with uncertainty. Without undermining the importance of further developing the prediction-reaction perspective, this study suggests an alternative approach where SC behavior is less dependent on the certainty of our knowledge about the environment and its changes.

This study suggests integrating the concepts of efficiency and resilience to enhance each other based on synergetic effects. Calling for the development of a new perspective in SC disruption management, i.e., low-certainty-need (LCN) SCs, this study identified two key LCN SC principles, i.e.,

- design and implementation of robust and resilient SCs focusing on the SC's ability to efficiently operate *regardless of environmental changes*,
- reduction of the re-planning efforts for disruption recovery with the help of efficient *proactive* robustness and recovery.

These two principles aim at utilizing a kind of a level strategy in the SC risk management as an analogy to Sales&Operations planning and as an opposite to the chase strategy in Sales&Operations planning which is based on continuous process adjustments on environmental changes. At the same time, we underline that the LCN SC concept is not equivalent to SC robustness. It is comprised of both robustness and resilience but rather from a proactive perspective with the help of embedding changeability and adaptability in the SC structural, process and parametric designs.

Furthermore, this study identified three key LCN SC characteristics, i.e.,

- structural complexity reduction,
- process and resource utilization flexibility, and
- non-expensive parametric redundancy.

These principles characteristics form the LCN SC framework and are also used to identify missing themes and new research questions contributing to a better understanding of the SC disruption risk phenomenon. More specifically, new research perspectives have been considered, such as risk exposure identification of consolidation nodes in SCs, the impact of digitalization and Industry 4.0 on SC flexibility, and network redundancy optimization.

In summary, the contributions of this study are (1) the development of a three-component framework, "structural variety – process flexibility – parametric redundancy," to facilitate the creation of a theory of LCN SCs, (2) an introduction of a literature analysis framework that considers the LCN SC perspectives, and (3) a sentiment on how to implement the LCN SC framework in practice.

The results presented are subject to some limitations. First, in each SC unique specific features exist that set limits on the generalizable recommendations without considering specifics such as business sectors, demand patterns, inventory turnover practices, and customer expectations (to name a few). Second, subjectivity in the literature analysis directly influences the LCN SC network composition and the resulting implementation recommendations. For example, some approaches to SC risk analysis, such as conditional value-at- risk, have not been included in the analysis due to the limited length of the paper. Third, the analysis in this paper could be extended by considering competitive behaviors in the SCs, combinations of fuzzy-probabilistic concepts, and dedicated meta-heuristics algorithms to cope with disruptions. Finally, a more detailed analysis of new developments in artificial intelligence, business analytics and smart manufacturing could extend the scope of this study. With regards to these limitations, we still believe that the results of this study may outline some new ideas in SC disruption management that can be used in both qualitative and quantitative research in the next years.

Acknowledgement

The authors thank the associate editor and two anonymous referees for their invaluable comments that helped us in manuscript improvement immensely. The authors also thank Professor Christopher Tang (UCLA) for his comments on the preliminary version of this paper that helped us to better shape main ideas of the framework developed.

References

Adenso-Díaz, B., Mar-Ortiz J., & S. Lozano (2018). Assessing supply chain robustness to links failure. International Journal of Production Research, DOI 10.1080/00207543.2017.1419582

Akkermans, H., van Wassenhove L.N. (2018). Supply chain tsunamis: Research on low probability high impact disruptions. Journal of Supply Chain Management, 54(1), 64-76.

Allesina, S., A. Azzi, D. Battini, and A. Regattieri (2010). Performance Measurement in Supply Chains: New Network Analysis and Entropic Indexes. International Journal of Production Research 48: 2297–2321.

Ambulkar, S., J. Blackhurst, S. Grawe. (2015). Firm's resilience to supply chain disruptions: Scale development and empirical examination, Journal of Operations Management, 33(34), 111–122.

Ang, E., Iancu, D., & Swinney, R. (2017). Disruption Risk and Optimal Sourcing in Multitier Supply Networks. Management Science, 63(8), 2397-2419.

Arkhipov A., Ivanov, D. (2011). An entropy-based approach to simultaneous analysis of supply chain structural complexity and adaptation potential, International Journal of Shipping and Transport Logistics, 3(2), 180-197.

Aven T. (2017). How some types of risk assessments can support resilience analysis and management. Reliability Engineering and System Safety 167, 536–543.

Babich, V., Burnetas, A.N., Ritchken, P.H. (2007). Competition and diversification effects in supply chains with supplier default risk? Manufacturing Service and Operations Management, 9(2), 123–146.

Bakal I.S., Z.P. Bayındır, D.E. Emer (2017). Value of disruption information in an EOQ environment. European Journal of Operational Research, 263, 446–460.

Bakshi, N., P.R. Kleindorfer (2009). Co-opetition and investment for supply-chain resilience, Production and Operations Management, 18(6), 583–603.

Basole, R.C. and Bellamy, M.A., Supply Network Structure, Visibility, and Risk Diffusion: A Computational Approach, Decision Sciences, 45(4), 1–49, 2014.

Behzadi, G., M.J. O'Sullivan, T.L. Olsen & A. Zhang (2018). Allocation flexibility for agribusiness supply chains under market demand disruption. International Journal of Production Research, 56(10), 3524-3546.

Behzadi, G., M. J. O'Sullivan, T. L. Olsen, F. Scrimgeour, A. Zhang (2017) Robust and resilient strategies for managing supply disruptions in an agribusiness supply chain. International Journal of Production Economics, 191, 207-220.

Bhamra R., Dani S., Burnard K. (2011). Resilience: the concept, a literature review and future directions. Int J Prod Res 49(15):5375–93

Blackhurst, J., Craighead, C.W., Elkins D., and Handfield, R. (2005). An empirically derived agenda of critical research issues for managing supply-chain disruptions. International Journal of Production Research, 43(19), 4067-4081.

Blackhurst, J., K. S. Dunn, and C. W. Craighead. (2011). An empirically derived framework of global supply resiliency. Journal of Business Logistics 32(4): 374–391.

Bode, C., S.M. Wagner, Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions, Journal of Operations Management 36, 215-228, 2015.

Brandon-Jones, E., Squire, B., Autry, C. W. and Petersen, K. J. (2014), "A Contingent Resource-Based Perspective of Supply Chain Resilience and Robustness". Journal of Supply Chain Management, 50, 55–73.

Carbonara N., Pellegrino R. (2017). How do supply chain risk management flexibility-driven strategies perform in mitigating supply disruption risks? International Journal of Integrated Supply Management, 11(4), 354-379.

Cats O., Koppenol G.-J., Warnier M. (2017). Robustness assessment of link capacity reduction for complex networks: Application for public transport systems. Reliability Engineering and System Safety 167, 544–553.

Chan JCC, Kroese DP. (2011). Rare-event probability estimation with conditional Monte Carlo. Annals of Operations Research, 189(1), 43–61.

Chen, Q., X. Li, and Y. Ouyang. (2011). Joint inventory-location problem under the risk of probabilistic facility disruptions. Transportation Research Part B: Methodological, 45(7): 991–1003.

Chen, X., Z Xi, P Jing (2017) A Unified Framework for Evaluating Supply Chain Reliability and Resilience. IEEE Transactions on Reliability, 66(4), 1144 – 1156.

Chopra, S., Sodhi, M.S., 2004. Managing risk to avoid supply-chain breakdown. MIT Sloan Management Review 46, 52–61.

Chopra, S., and M. S. Sodhi. (2014). Reducing the risk of supply chain disruptions. *MIT Sloan Management Review* 55(3): 73–80.

Chowdhury, M.H., M. Quaddus. (2017) Supply chain resilience: Conceptualization and scale development using dynamic capability theory. International Journal of Production Economics, 188, 185-204.

Calleja, G., A. Corominas, C. Martínez-Costa & R. de la Torre (2018). Methodological approaches to supply chain design. International Journal of Production Research, forthcoming

Craighead, C.W., Blackhurst, J., Rungtusanatham, M.J. and Handfield, R.B. (2007), "The severity of supply chain disruptions: design characteristics and mitigation capabilities". Decision Sciences, Vol. 38 No. 1, pp. 131-156.

DHL (2018). https://resilience360.com/ (accessed on February 4, 2018)

Dolgui, A., Ivanov, D., Sokolov, B. (2018). Ripple Effect in the Supply Chain: An Analysis and Recent Literature. International Journal of Production Research, 56(1-2), 414-430.

Dunke F., Heckmann I., Nickel S., Saldanha-da-Gama F. (2018). Time traps in supply chains: Is optimal still good enough? European Journal of Operational Research, 264, 813-829.

Fahimnia B, Tang CS, Davarzani H, Sarkis J (2015) Quantitative Models for Managing Supply Chain Risks: A Review. Eur J Oper Res 247(1):1-15.

Fisher ML (1997) What is the right supply chain for your product? Harv Bus Rev march–april: 83–93

Geng L., Xiao R. (2017). Outer synchronization and parameter identification approach to the resilient recovery of supply network with uncertainty. Physica A: Statistical Mechanics and its Applications, 482, 407-421.

Giannoccaro I., Nair A., Choi T. (2017). The Impact of Control and Complexity on Supply Network Performance: An Empirically Informed Investigation Using NK Simulation Analysis. Decision Science, published online.

Ghavamifar A., Makui, A., Taleizadeh, A.A. (2018). Designing a resilient competitive supply chain network under disruption risks: A real-world application. Transportation Research Part E: Logistics and Transportation Review, 115: 87-109

Gunasekaran, A., N. Subramanian, S. Rahman, Supply chain resilience: role of complexities and strategies, International Journal of Production Research, 53(22), 6809-6819, 2015.

Gupta V., He B., Sethi S.P. (2015). Contingent sourcing under supply disruption and competition. International Journal of Production Research, 53(10), 3006-3027.

Gurnani H, Mehrotra A, Ray S (2012) Supply Chain Disruptions: Theory and Practice of Managing Risk. Springer, London

Habermann, M., J. Blackhurst and A. Y. Metcalf (2015) Keep Your Friends Close? Supply Chain Design and Disruption Risk. Decision Sciences, 46(3), 491–526.

Haimes YY. (2009). On the definition of resilience in systems. Risk Analysis, 29:498–501.

Han, J., Shin, K.S. (2016) Evaluation mechanism for structural robustness of supply chain considering disruption propagation. International Journal of Production Research 54(1):135-151.

Handfield RB, McCormack K (2008) Supply Chain Risk Management: Minimizing Disruptions in Global Sourcing. Auerbach Publications

Harremoës, P., and F. Topsøe. 2001. Maximum Entropy Fundamentals. Entropy 3 (3): 191–226.

He, B., Huang, H., & Yuan, K. (2016). Managing supply disruption through procurement strategy and price competition. *International Journal of Production Research, 54*(7), 1980-1999

He, J, F Alavifard, D Ivanov, Jahani H. (2018). A real-option approach to mitigate disruption risk in the supply chain. Omega: The International Journal of Management Science, https://doi.org/10.1016/j.omega.2018.08.008.

Heckmann I (2016) Towards Supply Chain Risk Analytics. Springer-Gabler, Wiesbaden

Ho, W., T. Zheng, H. Yildiz & S. Talluri. Supply chain risk management: a literature review. International Journal of Production Research, 53(16), 5031-5069, 2015.

Hu, X., H. Gurnani, L. Wang (2013). Managing risk of supply disruptions: Incentives for capacity restoration, Production and Operations Management, 22(1), 137–150.

Hu, B., & Kostamis, D. (2015). Managing Supply Disruptions when Sourcing from Reliable and Unreliable Suppliers. *Production and Operations Management, 24*(5), 808-820.

Ivanov, D., B. Sokolov, J. Kaeschel (2010) A multi-structural framework for adaptive supply chain planning and operations with structure dynamics considerations, European Journal of Operational Research, 200, 409–420.

Ivanov D. (2017a) Simulation-based ripple effect modelling in the supply chain. International Journal of Production Research, 55(7), 2083-2101

Ivanov D. (2018a). Revealing interfaces of supply chain resilience and sustainability: a simulation study. International Journal of Production Research, 56(10), 3507-3523.

Ivanov D. (2017b). Simulation-based single vs dual sourcing analysis in the supply chain with consideration of capacity disruptions, Big Data and demand patterns. International Journal of Integrated Supply Management, 11(1), 24-43.

Ivanov D., Rozhkov M. (2017). 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. Annals of Operations Research, published online.

Ivanov D., Sokolov B., Dolgui A. (2014a). The Ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management, International Journal of Production Research, 52(7), 2154-2172.

Ivanov D., Sokolov, B., & Pavlov, A. (2014b). Optimal distribution (re)planning in a centralized multi-stage network under conditions of ripple effect and structure dynamics. European Journal of Operational Research, 237(2), 758–770.

Ivanov D., Tsipoulanidis A., Schönberger J. (2017a). Global Supply Chain and Operations Management, Springer, 1st Ed.

Ivanov, D., Arkhipov A. (2011) Analysis of structure adaptation potential in designing supply chains in an agile supply chain environment, International Journal of Integrated Supply Management, 6(2), 165-180.

Ivanov D., Pavlov A., Pavlov D., Sokolov B. (2017b). Minimization of disruption-related return flows in the supply chain, International Journal of Production Economics, 183, 503-513.

Ivanov D., Sokolov B., Pavlov, A. (2013). Dual problem formulation and its application to optimal redesign of an integrated production-distribution network with structure dynamics and ripple effect considerations, *International Journal of Production Research*, 51(18), 5386-5403.

Ivanov, D. (2018b). Structural Dynamics and Resilience in Supply Chain Risk Management. Springer, New York.

Ivanov, D., B. Sokolov, A. Pavlov, A. Dolgui, D. Pavlov, Disruption-driven supply chain (re)-planning and performance impact assessment with consideration of pro-active and recovery policies, Transportation Research: Part E, 90, 7-24, 2016.

Ivanov, D., B. Sokolov, Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis, and adaptation of performance under uncertainty, European Journal of Operational Research, 224(2), 313–323, 2013.

Ivanov, D., Dolgui A., Sokolov B., Ivanova M. (2017c). Literature review on disruption recovery in the supply chain. International Journal of Production Research, 55(20), 6158-6174.

Ivanov, D., Dolgui, A., Sokolov, B. (2018). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. International Journal of Production Research, https://doi.org/10.1080/00207543.2018.1488086

*Ivanov, D., Arkhipov A. (*2011) Analysis of structure adaptation potential in designing supply chains in an agile supply chain environment, **International Journal of Integrated Supply Management,** 6(2), 165-180.

Jain, V., S. Kumar, U. Soni & C. Chandra (2017) Supply chain resilience: model development and empirical analysis. International Journal of Production Research, 55(22), 6779-6800.

Jüttner, U. and Maklan, S. (2011), "Supply chain resilience in the global financial crisis: an empirical study". Supply Chain Management: An International Journal, Vol. 16 No. 4, pp. 246-259.

Kamalahmadi, M., M. Mellat-Parast, Developing a resilient supply chain through supplier flexibility and reliability assessment, International Journal of Production Research, 54(1), 302-321, 2016

Khojasteh, Y (2018) (Ed.) Supply chain risk management. Springer Singapore.

Kim, S.H., B. Tomlin, Guilt by association: Strategic failure prevention and recovery capacity investments, Management Science, 59(7), 1631–1649, 2013.

Kim, Y., Y.S.Chen, K. Linderman, Supply network disruption and resilience: A network structural perspective, Journal of Operations Management, 33–34, 43–59, 2015.

Kleindorfer, P. R., & Saad, G. H. (2005). Managing disruption risks in supply chains. Production and Operations Management, 14(1), 53–68.

Klibi W., & Martel A. (2012). Modeling approaches for the design of resilient supply networks under disruptions. International Journal of Production Economics, 135 (2), 882-898.

Kumar, M., Basu, P., Avittathur B. (2018). Pricing and sourcing strategies for competing retailers in supply chains under disruption risk. European Journal of Operational Research, 265(2), 533-543.

Levner E., Ptuskin A. (2017). Entropy-based model for the ripple effect: managing environmental risks in supply chains. International Journal of Production Research, 56(7), 2539-2551

Li, Q., B. Zeng, and A. Savachkin. (2013). Reliable facility location design under disruptions. Computers & Operations Research 40(4): 901–909.

Li, T., Sethi, S., & Zhang, J. (2017). Mitigating Supply Uncertainty: The Interplay between diversification and pricing. *Production and Operations Management, 26*(3), 369-388

Liberatore F, Scaparra M.P., Daskin M.S. (2012). Hedging against disruptions with ripple effects in location analysis. Omega, 40, 21–30

Lim M., Daskin M. S., Bassamboo A., and Chopra S. (2010). A facility reliability problem: Formulation, properties and algorithm. Naval Research Logistics, 57(1), 58–70.

Lim M.K., Bassamboo A., Chopra S., and Daskin M. S. (2013). Facility location decisions with random disruptions and imperfect estimation. Manufacturing and Service Operations Management, 15(2), 239–249.

Lu M., Huang S., Shen Z.J.M (2011). Product substitution and dual sourcing under random supply failures. Transportation Research Part B 45 (2011) 1251–1265.

Macdonald, J.R., Zobel, C.W., Melnyk, S.A., Griffis, S.E., (2018). Supply chain risk and resilience: theory building through structured experiments and simulation. International Journal of Production Research, 56(12), 4337-4355.

Melnyk, S.A., Closs, D.J., Griffis, S.E., Zobel, C.W., Macdonald, J.R. (2014), "Understanding supply chain resilience". Supply Chain Management Review, Vol.18 No.1, pp. 34–41.

Mizgier, K.J., Jüttner, M., Wagner, S.M. (2013). Bottleneck Identification in Supply Chain Networks. International Journal of Production Research, 51(5), 1477-1490.

Mizgier, K.J., Wagner, S. M., Jüttner, M (2015). Disentangling Diversification in Supply Chain Networks. International Journal of Production Economics, 162, 115-124,

Mizgier, K. J. (2017). Global Sensitivity Analysis and Aggregation of Risk in Multi-Product Supply Chain Networks. International Journal of Production Research, 55(1), 130-144.

Monostori J. (2018). Supply chains' robustness: Challenges and opportunities. Procedia CIRP 67, 110 – 115

Nair, A., J.M. Vidal (2011). Supply network topology and robustness against disruptions – An investigation using a multi-agent model, International Journal of Production Research, 49(5), 1391–1404.

Namdar, J., X. Li, R. Sawhney, N. Pradhan (2018) Supply chain resilience for single and multiple sourcing in the presence of disruption risks. International Journal of Production Research. DOI: 10.1080/00207543.2017.1370149

Ojha, R., Ghadge, A., Tiwari M.K. & U. S. Bititci (2018). Bayesian network modelling for supply chain risk propagation. International Journal of Production Research, DOI: 10.1080/00207543.2018.1467059

Park J., Seager T.P., Rao PSC, Convertino M., Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. Risk Analysis, 33(3):356–367.

Pavlov A., Ivanov D., Dolgui A., Sokolov B. (2018) Hybrid fuzzy-probabilistic approach to supply chain resilience assessment. IEEE Transactions on Engineering Management, 65(2), 303-315.

Peng, P., L. V. Snyder, A. Lim, Z. Liu. (2011). Reliable logistics networks design with facility disruptions. Transportation Research Part B: Methodological 45(8): 1190–1211.

Pettit, T.J., Croxton, K.L. and Fiksel, J. (2013), "Ensuring supply chain resilience: development and implementation of an assessment tool", Journal of Business Logistics, Vol.34 No.1, pp. 46-76.

Quang HT, Hara Y. (2017): Risks and performance in supply chain: the push effect, *International Journal of Production Research*, DOI: 10.1080/00207543.2017.1363429

Rafiei M., Mohammadi M., Torabi S. (2013). Reliable multi period multi product supply chain design with facility disruption. Decision Science Letters 2(2): 81–94.

Rangel, D. A., T. K. de Oliveira, and M. S. Alexandre. 2015. "Supply Chain Risk Classification: Discussion and Proposal." International Journal of Production Research 53 (22): 6868–6887.

Ravindran, A.R., Bilsel, R.U., Wadhwa, V., Yang, T., 2012. Risk adjusted multicriteria supplier selection models with applications. International Journal of Production Research 48(2), 405–424.

Reyes Levalle, R., Nof, S.Y., Resilience in supply networks: Definition, dimensions, and levels. Annual Reviews in Control, 43, 224-236, 2017.

Rezapour, S., Farahani, R., Pourakbar, M. (2017). Resilient supply chain network design under competition: a case study. European Journal of Operational Research, 259(3), 1017-1035.

Samani, M.R.G. & Hosseini-Motlagh, SM. (2018) An enhanced procedure for managing blood supply chain under disruptions and uncertainties. Annals of Operation Research. https://doi.org/10.1007/s10479-018-2873-4

Sawik T. (2016). On the risk-averse optimization of service level in a supply chain under disruption risks. International Journal of Production Research, 54(1), 98-113.

Sawik T. A portfolio approach to supply chain disruption management. International Journal of Production Research, 55(7), 1970-1991, 2017.

Scheibe K.P., Blackhurst, J. Supply chain disruption propagation: a systemic risk and normal accident theory perspective. International Journal of Production Research, 56(1-2), 43-59.

Schmitt A.J., & Singh M. (2012). A quantitative analysis of disruption risk in a multi-echelon sup-ply chain. International Journal of Production Economics, 139(1), 23–32.

Schmitt T.G., Kumar S., Stecke K.E., Glover F.W., Ehlen M.A. (2017). Mitigating disruptions in a multi-echelon supply chain using adaptive ordering. Omega, 68, 185-198.

Seifert RW, Langenberg KU (2011) Managing business dynamics with adaptive supply chain portfolios. European Journal of Operational Research 215(3): 551-562

Shao, X.F., M. Dong. (2012). Supply disruption and reactive strategies in an assemble-to-order supply chain with time-sensitive demand. IEEE Transactions on Engineering Management 59(2): 201–212.

Sheffi, Y. (2005). The resilient enterprise: overcoming vulnerability for competitive advantage. Cambridge, MA: MIT Press.

Shukla N., Kiridena S. (2016) A fuzzy rough sets-based multi-agent analytics framework for dynamic supply chain configuration, International Journal of Production Research, 54:23, 6984-6996

Simchi-Levi D., Schmidt W., Wei Y., Zhang P.Y., Combs K., Ge Y., Gusikhin O., Sander M., Zhang D. (2015) Identifying Risks and Mitigating Disruptions in the Automotive Supply Chain. Interfaces, 45(5), 375-390.

Simchi-Levi D., H. Wang and Y. Wei (2018). Increasing Supply Chain Robustness through Process Flexibility and Inventory. Production and Operations Management, forthcoming.

Snyder, L.V., M. S. Daskin. (2005). Reliability models for facility location: The expected failure cost case. Transportation Science 39: 400–416.

Snyder, L. V., Z. Atan, P. Peng, Y. Rong, A. Schmitt, and B. Sinsoysal, 2016. OR/MS models for supply chain disruptions: A review, IIE Transactions, 48(2), 89-109

Sodhi MS, Son BG, Tang C (2012) Researchers' perspectives on supply chain risk management. Prod Oper Manag 21(1):1-13

Sodhi MS., Tang C.S. (2012). Managing supply chain risk. Springer, NY

Sokolov, B., D. Ivanov, A. Dolgui, A. Pavlov (2016). Structural quantification of the ripple effect in the supply chain. International Journal of Production Research, 54(1), 152-169.

Song, J.M., Chen W., & Lei L. (2018). Supply chain flexibility and operations optimisation under demand uncertainty: a case in disaster relief. International Journal of Production Research, 56(10), 3699-3713.

Spiegler V., Naim M. and Wikner J. (2012). A control engineering approach to the assessment of supply chain resilience. International Journal of Production Research, 50, 6162-6187.

Spiegler, VLM, Naim, M. M., Towill, D. R., Wikner, J. (2016). The value of nonlinear control theory in investigating the underlying dynamics and resilience of a grocery supply chain. International Journal of Production Research, 54(1):265-286

Tang C.S. (2006). Perspectives in supply chain risk management. International Journal of Production Economics, 103, 451-488.

Tang C.S. (2007) Robust strategies for mitigating supply chain disruptions. International Journal of Logistics: Research and Applications 9(1), 33-45.

Tang, L., K. Jing, J. He, H.E. Stanley (2016). Complex interdependent supply chain networks: Cascading failure and robustness, Physica A, 443, 58–69.

Tang, O., S. N. Musa (2011). Identifying Risk Issues and Research Advancements in Supply Chain Risk Management. International Journal of Production Economics 133: 25–34.

Tomlin, B. T. (2006). On the value of mitigation and contingency strategies for man- aging supply chain disruption risks. Management Science, 52 (5), 639–657.

Torabi S.A., Baghersad M., Mansouri S.A. (2015). Resilient supplier selection and order allocation under operational and disruption risks. Transportation Research Part E: Logistics and Transportation Review, 79, 22–48.

Tsai, W. (2016). A dynamic sourcing strategy considering supply disruption risks. *International Journal of Production Research, 54*(7), 2170-2184

Tukamuhabwa B.R., Stevenson M., Busby J. & Zorzini M. (2015). Supply chain resilience: definition, review and theoretical foundations for further study. International Journal of Production Research, 53(18), 5592-5623.

Ulutas, A., Shukla, N., Kiridena S., & Gibson P. (2016) A utility-driven approach to supplier evaluation and selection: empirical validation of an integrated solution framework, International Journal of Production Research, 54:5, 1554-1567

Wang, X., Disney, S. M., 2012. Stability analysis of constrained inventory systems. European Journal of Operational Research 223, 86–95.

Wang, Z., Wang, X., Ouyang, Y., 2015. Bounded growth of the bullwhip effect under a class of nonlinear ordering policies. European Journal of Operational Research 247 (1), 72 – 82.

Wilson M.C. (2007). The impact of transportation disruptions on supply chain performance. Transportation Research Part E: Logistics and Transportation Review, 43, 295–320.

Xia, Y., Yang, M. H., Golany, B. , Gilbert, S. M. , & Yu, G. (2004). Real-time disruption management in a two-stage production and inventory system. IIE Transactions, 36 (2), 111–125.

Yadav SR, Mishra N, Kumar V, Tiwari MK (2011). A framework for designing robust supply chains considering product development issues. International Journal of Production Research, 49(20): 6065–6088.

Yang, Z., & Babich, V. (2015). Does a procurement service provider generate value for the buyer through information about supply risks? Management Science, 61 (5), 979–998.

Yang, Z., Aydin, G., Babich, V. , & Beil, D. R. (2009). Supply disruptions, asymmetric information, and a backup production option. Management Science, 55 (2), 192–20.

Yang, Z., Aydin, G., Babich, V., & Beil, D. R. (2012). Using a dual-sourcing option in the presence of asymmetric information about supplier reliability: Competition vs. diversification. Manufacturing & Service Operations Management, 14 (2), 202–217.

Yildiz H., J. Yoon, S. Talluri and W. Ho (2016). Reliable Supply Chain Network Design. Decision Sciences, 47(4), 661–698.

Yin Z. & C. Wang (2018) Strategic cooperation with a backup supplier for the mitigation of supply disruptions. International Journal of Production Research, 56(12), 4300-4312

Yin, Z., X Guan, L Xiao (2017). Managing global sourcing with disruption risks in an assemble-to-order system. Transportation Research Part E, 108, 1-17.

Yoon, J., Narasimhan R. & Kim M.K. (2018b). Retailer's sourcing strategy under consumer stockpiling in anticipation of supply disruptions, International Journal of Production Research, 56(10), 3615-3635

Yoon, J., S. Talluri, H. Yildiz, W Ho (2018a). Models for Supplier Selection and Risk Mitigation: A Holistic Approach. International Journal of Production Research, 56(10), 3636-3661

Yu G., Li F. & Yang Y. (2017). Robust supply chain networks design and ambiguous risk preferences. International Journal of Production Research, 55(4), 1168-1182.

Zobel, C.W. and Khansa, L. (2014), "Characterizing multi-event disaster resilience", Computers and Operations Research, Vol. 42, pp. 83–94.

Zhu, S. (2015). Analysis of dual sourcing strategies under supply disruptions. *International Journal of Production Economics, 170*, 191-203.

Appendix 1 Literature classification scheme

Analysis levels		**Proactive stage**			**Reactive stage**	
Network structure and variety	I	**Co**mplexity	A, B, C, D, E, F	I	**Co**mplexity	A, B, C, D, E, F
		Centralisation			**Ce**ntralisation	
	1	**Di**versification		**7**	**Di**versification	
		Localisation			**Lo**calisation	
	II	**Co**mplexity	A, B, C, D, E, F	II	**Co**mplexity	A, B, C, D, E, F
		Centralisation			**Ce**ntralisation	
	2	**Di**versification		**8**	**Di**versification	
		Localisation			**Lo**calisation	
Process flexibility	I	**Ba**ckup/dual s.	A, B, C, D, E, F	I	**Ba**ckup/dual s.	A, B, C, D, E, F
		Postponement			**Po**stponement	
	3	**Pr**oduct subst.		**9**	**Pr**oduct subst.	
		Coordination			**Co**ordination	
	II	**Ba**ckup/dual s.	A, B, C, D, E, F	II	**Ba**ckup/dual s.	A, B, C, D, E, F
		Postponement			**Po**stponement	
	4	**Pr**oduct subst.		**10**	**Pr**oduct subst.	
		Coordination			**Co**ordination	
Parametric redundancy	I	**In**ventory	A, B, C, D, E, F	I	**In**ventory	A, B, C, D, E, F
		Capacity			**Ca**pacity	
	5	**Le**ad time		**11**	**Le**ad time	
	II	**In**ventory	A, B, C, D, E, F	II	**In**ventory	A, B, C, D, E, F
		Capacity			**Ca**pacity	
	6	**Le**ad time		**12**	**Le**ad time	

Legend:

I – Supply Chain Structural Design

II – Supply Chain Process Planning and Control

1 –12 – Research field numbers

A – F – Methodologies:

A – Mathematical Optimization (deterministic mixed-integer, stochastic, robust, goal and fuzzy optimization)

B – Simulation (discrete-event simulation, agent-based simulation, system dynamics)

C – Game Theory (cooperative/non-cooperative, dynamic differential and symmetric/asymmetric (incomplete information) games)

D – Control Theory (optimal control, model-predictive control, feedback control)

E – Reliability Theory (probabilistic, statistical, logic and graph models)

F – Hybrid Methodology

Coding example for Ivanov D., Sokolov, B., & Pavlov, A. (2014b). Optimal distribution (re)planning in a centralized multi-stage network under conditions of ripple effect and structure dynamics. European Journal of Operational Research, 237(2), 758–770:

10 – II – Ba – F:AD – this study focuses on the SC planning level and the impact of backup sourcing at the process recovery stage using a hybrid optimization-control theory methodology