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Operations Research & Management Science

Dmitry Ivanov
Alexandre Dolgui
Boris Sokolov *Editors*

Handbook of Ripple Effects in the Supply Chain

Springer

International Series in Operations Research & Management Science

Volume 276

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ISSN 0884-8289 ISSN 2214-7934 (electronic)
International Series in Operations Research & Management Science
ISBN 978-3-030-14301-5 ISBN 978-3-030-14302-2 (eBook)
https://doi.org/10.1007/978-3-030-14302-2

Library of Congress Control Number: 2019932624

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Preface

Purpose and Content of the Book

This handbook comprises recent developments in a new research field of the ripple effects in supply chains (SC). The chapters of this handbook are written by leading experts in SC risk management and resilience. For the first time, the chapters present a multiple-faceted view of the ripple effect in SCs, while considering organization, optimization, and informatics perspectives. The ripple effect occurs when an SC disruption cascades downstream, rather than remaining localized, and impacts the performance of the SC. The ripple effect considers structural network dynamics in the SC that is initiated by a severe disruption (or a series of disruptions) and describes the propagation of this disruption downstream the SC in terms of switching off some nodes and arcs in the network, e.g., due to material shortage. The impacts of the ripple effect might include lower revenues, delivery delays, loss of market share and reputation, or decreases in stock returns—the costs of these negative impacts can be devastating.

This book offers an introduction to the ripple effect in the supply chain for larger audience. The book delineates major features of the ripple effect and methodologies to mitigate the supply chain disruptions and recover in case of severe disruptions. The book reviews recent quantitative literature that tackled the ripple effect and gives a comprehensive vision of the state of the art and perspectives. The methodologies comprise mathematical optimization, simulation, control theoretic, and complexity and reliability research. The book observes the reasons and mitigation strategies for the ripple effect in the supply chain 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 said area in recent years, some crucial research avenues have been identified for the near future.

The book is expected to furnish fresh insights for supply chain management and engineering regarding the following questions:

- In what circumstance does one failure cause other failures?
- Which structures of the supply chain are especially prone to the ripple effect?
- What are the typical ripple effect scenarios and what is the most efficient way to respond to them?

Given these reflections, numerous ways to apply quantitative analysis to ripple effect modelling arise. Several research gaps might be addressed by the ability to dynamically change parameters during experiments and to observe how these changes impact performance in real time, e.g., considering:

- disruption propagation in the supply chain;
- dynamic recovery policies;
- gradual capacity degradation and recovery;
- multiple performance impact dimensions including financial, customer and operational performance.

Distinctive Features

- It considers ripple effect in the supply chain from interdisciplinary perspective.
- It offers an introduction to the ripple effect mitigation and recovery policies in the framework of disruption risk management in the supply chains for larger audience.
- It integrates management and engineering perspectives on disruption risk management in the supply chain.
- It presents innovative optimization and simulation models for real-life management problems.
- It considers examples from both industrial and service supply chains.
- It reveals decision-making recommendations for tackling disruption risks in the supply chain in proactive and reactive domains.

Target Audience

Management and engineering graduate and Ph.D. students, supply chain and operations management professionals, industrial engineers, operations and supply chain risk researchers.

Berlin, Germany — Dmitry Ivanov
Nantes, France — Alexandre Dolgui
St. Petersburg, Russia — Boris Sokolov

Acknowledgements

The author gratefully acknowledges all those who have helped bring this book to publication. First and foremost, we have greatly benefited from the wealth of a vast array of published materials on the subject of supply chain risk management and associated topics. We would also like to thank the authors of each of the chapters. The content of this book has benefited immensely from their valuable insights, comments, and the suggestions of many reviewers. With regards to manuscript preparation, we thank Ms. Meghan Stewart for a thorough proofreading of the manuscript, as well as Ms. Tamara Erdenberger for her technical assistance. Finally, we wish to thank the editors, Neil Levine and Dr. Camille Price, and the entire Springer production team for their assistance and guidance in the successful completion of this book. Last, but not least—we thank our families for their enormous support during the writing and development of this book.

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About the Editors

Prof. Dr. habil. Dr. Dmitry Ivanov is Professor of Supply Chain Management at Berlin School of Economics and Law (HWR Berlin), Deputy Director and Executive Board Member of Institute for Logistics, and Director of master program in Global Supply Chain and Operations Management at HWR Berlin since 2011. He is leading working groups, tracks, and sessions on Supply Chain Risk Management and Resilience in global research communities. He is a recipient of many prestigious Best Paper awards. He edits the *International Journal of Integrated Supply Management*. His publication list includes around 300 publications, including 65 research papers in prestigious academic journals and leading books *Global Supply Chain and Operations Management* and *Structural Dynamics and Resilience in Supply Chain Risk Management*.

He has been *teaching* classes for more than 20 years in operations management, production and supply management, supply chain management, logistics, management information systems, and strategic management at undergraduate, master's, Ph.D., and executive M.B.A. levels at different universities worldwide in English, German, and Russian. He has given guest lectures, presented scholarly papers and has been a Visiting Professor at numerous universities in Asia, Europe, and North America. He has been involved with collaborative educational projects with many universities worldwide. He is leading anyLogistix educational virtual lab and published handbooks on using AnyLogic and anyLogistix software in management education.

His *research* explores supply chain structural dynamics and control, with an emphasis on supply chain risk analytics, global supply chain design with disruption consideration, scheduling in Industry 4.0 systems, and digital supply chain. He is co-author of structural dynamics control methods for supply chain management. He applies mathematical programming, simulation, control and fuzzy theoretic methods. Based upon triangle "process-model-technology", he investigates the dynamics of complex networks in production, logistics, and supply chains. Most of his courses and research focuses on the interface of supply chain management, operations research, industrial engineering, and information technology.

His *academic* background includes industrial engineering, operations research, and applied control theory. He studied industrial engineering and production management in St. Petersburg and Chemnitz and graduated with distinction. He gained his Ph.D. (Dr.rer.pol.), Doctor of Science (Sc.D.), and Habilitation degrees in 2006 (TU Chemnitz), 2008 (FINEC St. Petersburg), and 2011 (TU Chemnitz), respectively. In 2005, he was awarded the German Chancellor Scholarship.

Prior to becoming an *academic*, he was mainly engaged in *industry and consulting*, especially for process optimization in manufacturing and logistics and ERP systems. His practical expertise includes numerous projects on the application of operations research and process optimization methods for operations design, logistics, scheduling, and supply chain optimization. Prior to joining the Berlin School of Economics and Law, he was Professor and Acting Chair of Operations Management at University of Hamburg.

Professor Ivanov's research has been published in various academic journals, including *Annals of Operations Research*, *Annual Reviews in Control*, *Computers and Industrial Engineering*, *European Journal of Operational Research*, *IEEE Transactions on Engineering Management*, *International Journal of Information Management*, *International Journal of Integrated Supply Management*, *International Journal of Production Research*, *International Journal of Production Economics*, *International Journal of Technology Management*, *International Journal of Systems Science*, *International Transactions in Operational Research*, *Journal of Scheduling, Omega, Transportation Research: Part E*, etc.

He has been Guest Editor of special issues in different journals, including *Annals of Operations Research*, *International Journal of Production Economics*, *International Journal of Production Research*, *International Transactions in Operations Research*, *International Journal of Information Management* and the *International Journal of Integrated Supply Management*. He co-edits *International Journal of Integrated Supply Management*. He is an Associate Editor and Editorial Board Member of the *International Journal of Production Research* and *International Journal of Systems Science* and Editorial Board member of several international and national journals, e.g., the *International Journal of Systems Science: Operations and Logistics* and the *International Journal of Inventory Research*.

He is Chairman of IFAC TC 5.2 "Manufacturing Modelling for Management and Control" and Co-Chairman of the IFAC TC 5.2 Working group "Supply Network Engineering". He has been member of numerous associations, including INFORMS, POMS, CSCMP, VHB, and GOR.

He regularly presents his research at scientific and industry events and welcomes new collaborations. He has been Chairman of IFAC MIM 2019 conference, advisory board member and IPC member of many international conferences, where he has organized numerous tracks and sessions (including IFAC MIM, INCOM, EURO, INFORMS, IFORS, OR, IFAC World Congress, and IFIP PRO-VE).
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Prof. Dr. habil. Alexandre Dolgui is a Distinguished Professor (Full Professor of Exceptional Class in France) and the Head of Automation, Production, and Computer Sciences Department at the IMT Atlantique (former Ecole des Mines de Nantes), France. His research focuses on manufacturing line design, production planning and supply chain optimization. His research is mainly based on exact mathematical programming methods and their intelligent coupling with heuristics and metaheuristics algorithms.

He is the co-author of 5 books, the co-editor of 16 books for conference proceedings, the author of 225 refereed journal papers, 27 editorials, and 28 book chapters, as well as the author of over 400 papers written for conference proceedings. He is the Editor-in-Chief of the *International Journal of Production Research*, an Area Editor of *Computers & Industrial Engineering*, and an Associate Editor of *Journal Européen des Systèmes Automatisés*. He is also past Associate Editor of *International Journal of Systems Science* (2005–2008), *IEEE Transactions on Industrial Informatics* (2006–2009), and *Omega-the International Journal of Management Science* (2009–2012), as well as having been the consulting Editor of the *International Journal of Systems Science* (2009–).

He is a member of editorial boards for 25 other journals, including the *International Journal of Production Economics*, *International Journal of Manufacturing Technology & Management*, *International Journal of Simulation & Process Modelling*, *International Journal of Engineering Management & Economics*, *Journal of Decision Systems*, *Journal of Mathematical Modelling & Algorithms*, *Journal of Operations and Logistics*, *Journal of Industrial Engineering and Management & Production Engineering Review*, *Decision Making in Manufacturing and Service*, *Risk and Decision Analysis*, etc. He is also a fellow of the European Academy for Industrial Management, a member of the board of the International Foundation for Production Research, Vice-Chair of IFAC TC 5.2 Manufacturing Modelling for Management and Control, a member of IFIP WG 5.7 Advances in Production Management Systems, IEEE System Council Analytics, and Risk Technical Committee, and Guest Editor of special issues of European Journal of Operational Research, International Journal of Production Research, International Journal of Production Economics, Omega-the International Journal of Management Science, Journal of Intelligent Manufacturing, Journal of Mathematical Modeling and Algorithms and Annual Reviews in Control. He was General Scientific Chair of the 12th IFAC symposium INCOM'06, Chairman of International Program Committee of SCM'02, MOSIM'04, INCOM'09, INCOM'12, IESM'13, MIM'13, INCOM'15, IESM'17, GSC'18 and MIM'19, and Chairman of Steering committee of MIM'16. He was also Chairman of the Organizing Committee of the International Conference MOSIM'01 and ROADEF'2011. In the last 10 years, he was a member of the Program Committees of over 200 International Conferences, etc. He has been responsible for the French national CNRS working group on Design of Production Systems (with about 336 individual members) and the regional project on Design and Management of Reconfigurable Manufacturing Systems. e-mail: alexandre.dolgui@imt-atlantique.fr

Prof. Dr. Eng. Boris Sokolov born in 1951, is Head of Laboratory of Information Technologies in System Analysis and Modeling at Saint Petersburg Institute of Informatics and Automation of the Russian Academy of Sciences (SPIIRAS). From 2006 to 2017, he was Deputy Director for research of SPIIRAS. In 2008, he became an honored scientist in Russia. He is a Laureate of the Prize of the Government of the Russian Federation in the field of science and technology (2013).

He received his M.Sc., Ph.D., Dr. Sc. Eng., and Prof. in 1974, 1983, 1993 and 1994, respectively. He is a founder of a new scientific direction in the field of automating the management processes of complex technical objects (CTO) associated with complex analysis and management of processes in critical applications.

The research interests of Prof. B. Sokolov are as follows: basic and applied research in integrated modeling, simulation and mathematical methods in scientific research, optimal control theory and mathematical models and methods of decision-making support in complex technical-organizational systems under uncertainties and with multi-criteria, implementations of RFID technology and mobile IT in supply chain management processes. Over the past years, Prof. Sokolov intensively developed an original applied theory of structural dynamics management. The reliability and validity of his conclusions and developments have been confirmed both internationally and within Russia by numerous publications, implementations, and testing.

The results of the research, conducted by him personally and his students, have been widely and diversely implemented both in scientific organizations and enterprises. Professor Sokolov and representatives of his scientific school have developed analytical methods, methods, algorithms, and techniques for integrated automated planning and control of their structural dynamics, which are resolved with minimal resources.

From 1999 to the present, he worked on a number of projects funded by the Russian Academy of Sciences, the Russian Foundation for Basic Research, the Russian Science Foundation, the Applied Problems Section of the Presidium of the Russian Academy of Sciences, and international organizations (EORD, CRDF).

Professor Sokolov has been actively teaching since 1982. Since 1999, he has been a Professor of St. Petersburg SUAI. He developed several original courses of lectures on the integrated modeling of the management processes of the structural dynamics of complex objects in various subject areas. He has supervised 10 candidates of technical sciences (Ph.D.) and 4 doctors of technical sciences (Dr. Habil.). Professor Sokolov is a member of the academic council of SPIIRAS and two dissertation councils, and has repeatedly been a member of the program committees at prestigious Russian and international conferences. He is a member of the Editorial Board of the International Journal of Integrated Supply Management, the Advisory Committee of the International Journal of Instrumentation, the International Journal of Information Technology, the Astronautics Federation, and the Academy of Navigation and Motion Control.

He is (co)-author of 7 monographs and books on system analysis, decision support systems, supply chain management and systems and control theory, and of more than 570 scientific works published in various academic journals, including the European

Journal of Operational Research, the International Journal of Manufacturing Technology and Management, the International Journal of Production Research, the Journal of Computer and Systems Sciences International, Differential Equations, Automation and Remote Control, and Annual Reviews in Control.

The works of Prof. Sokolov on this book were supported by the Russian Foundation for Basic Research (grants 16-29-09482-ofi-i, 17-11-01254, 17-29-07073-ofi-i, 18-07-01272, 19-08-00989), grant 074-U01 (ITMO University), state order of the Ministry of Education and Science of the Russian Federation №2.3135.2017/4.6, state research 0073–2018–0003, International project ERASMUS +, Capacity building in higher education, № 73751-EPP-1-2016-1-DE-EPPKA2-CBHE-JP, Innovative teaching and learning strategies in open modelling and simulation environment for student-centered engineering education’. e-mail: sokol@iias.spb.su

Introduction

Chapters in this Book

The Chapter "Ripple Effect in the Supply Chain: Definitions, Frameworks and Future Research Perspectives" by Dmitry Ivanov, Alexandre Dolgui, and Boris Sokolov begins the book. This chapter aims to delineate both major features of the ripple effect and methodologies for mitigating SC disruptions and recovering from severe disruptions. It presents an overview of the causes of the ripple effects and mitigation strategies. A framework for ripple effect control, comprised of redundancy, flexibility, and resilience, is developed. In addition, though a variety of valuable insights has been garnered in recent years, new research avenues and ripple effect taxonomies are identified for the near future. Special focus is directed toward SC risk analytics and the ripple effect in SCs.

Next, in the Chapter "A Multi-portfolio Approach to Integrated Risk-Averse Planning in Supply Chains under Disruption Risks", Tadeusz Sawik suggests a methodical approach to time- and space-integrated decision-making. In the context of SC disruptions, the portfolio is defined as the allocation of demand for parts among suppliers or the allocation of demand for products among production facilities. A disruptive event is assumed to impact both primary suppliers of parts and the firm primary assembly plant. Considering the integration of mitigation and recovery decisions over time and space, the author shows that the primary portfolios to be implemented before a disruptive event are optimized simultaneously via recovery portfolios for the aftermath period as well as the portfolios of both parts suppliers and product manufacturers in different geographic regions. Risk-averse solutions are obtained through conditional cost-at-risk and conditional service-at-risk measures. The findings indicate that when the objective is to optimize service level with no regard to costs, both supply and demand portfolios are more diversified. The author concludes that the proposed multi-portfolio approach enables time- and space-integrated decision-making that may help to better mitigate the impact of disruption propagation on SC performance, i.e., the ripple effect.

Virginia L. M. Spiegler, Mohamed M. Naim, and Junyi Lin focus their Chapter on "The Rippling Effect of Non-linearities". Using control theoretic tools, they show that nonlinearities can lead to unexpected dynamic behaviors in the SC that could then either trigger disruptions or make the response and recovery process more difficult. This chapter is particularly relevant for researchers wanting to learn more about the different types of nonlinearities that can be found in the SC, the existing analytical methods for dealing with each type of nonlinearity, and the potential direction of future research based on current knowledge in this field.

Jennifer Blackhurst and Kevin Scheibe devote their Chapter "Systemic Risk and the Ripple Effect in the Supply Chain" on the concept of systemic risk coupled with the impact of the ripple effect in the SC. They describe the dimensions of systemic risks as part of the nature of disruption, SC structure and dependence, and managerial decision-making. Moreover, the authors discuss interrelations between the ripple and bullwhip effects. The authors conclude that because disruptions frequently ripple through a system, a systemic risk perspective is crucial for understanding not only the nature of the disruption but also the effects of the structure of the SC and the consequences of choices made by decision makers.

In their Chapter "Leadership for Mitigating Ripple Effects in Supply Chain Disruptions: A Paradoxical Role", Iana Shaheen, Arash Azadegan, Robert Hooker, and Lorenzo Lucianetti analyze how leaders' adaptive decision-making (ADM) affects the extent of operational performance damage caused by different forms of SC disruptions. SC disruptions often sever multiple value-generating streams, creating a ripple effect across organizations. Reestablishing production links in a web of interorganizational exchanges requires careful examination of what is at stake for purchasing and supply managers. Using paradox and leadership theories, they offer hypotheses related to unexpected, complicated, and enduring SC disruptions. By empirically testing the hypotheses using secondary (financial) and primary (managerial assessment) data from a cross-section of 251 manufacturing firms, they show a concave curvilinear relationship between leader's ADM and operational damage from SC disruptions, suggesting that moderate levels of ADM are optimal. Higher ADM is particularly effective for diminishing ripple effects in the face of infrequent disruptions. On the other hand, low ADM is more effective in the face of unexpected and complicated disruptions.

In their Chapter "A Model of an Integrated Analytics Decision Support System for Situational Proactive Control of Recovery Processes in Service-Modularized Supply Chain", Dmitry Ivanov and Boris Sokolov consider the challenge recovery process, a disruptive event, planning of the recovery control policy, and implementation of this policy in the SC. These events are distributed in time and subject to SC structural and parametrical dynamics. In other words, environment, SC structure and the SC's operational parameters may change in the period between the planning of the recovery control policy and its implementation. As such, situational proactive control with combined use of simulation optimization and analytics is proposed to improve processes of transition between a disrupted and a restored SC state. Implementation of situational proactive control can reduce investments in robustness and increase resilience by obviating time traps in problems of transition process control. This chapter presents a decision support system model for situational proactive control of SC recovery processes based on a combination of optimization and analytics techniques. More specifically, three dynamic models are developed and integrated with each other, i.e., a model of SC material flow control, a model of SC recovery control, and a model of SC recovery control adjustment. The given models are developed within a cyber-physical SC framework based on an approach of service modularization.

In their Chapter "Bullwhip Effect of Multiple Products with Interdependent Product Demands", Srinivasan Raghunathan, Christopher S. Tang, and Xiaohang Yue present a study that extends current theory to provide insights for a firm that manufactures multiple products in a single product category with interdependent demand streams. This study finds that interdependency between demand streams plays a critical role in determining the existence and magnitude of the bullwhip effect. More importantly, the authors show that interdependency impacts whether the firm should manage ordering and inventory decisions at the category level or at the product level, and whether the bullwhip effect measure computed at the category level is informative or not.

The Chapter "Performance Impact Analysis of Disruption Propagations in the Supply Chain" by Dmitry Ivanov, Alexander Pavlov, and Boris Sokolov develops a method for quantifying the ripple effect in the SC with consideration of recovery policy. The performance impact index developed is then used to compare sales (revenue) in different SC designs to measure the estimated annual magnitude of the ripple effect. First, optimal SC recovery for two disruption scenarios is computed. Second, the performance impacts of disruptions for six proactive SC designs are assessed. Finally, the performance impact indexes of different SC designs are compared and conclusions are drawn about the ripple effect in these SC designs along with recommendations for the selection of a proactive strategy. The performance impact index developed can be used to assess how different markets are exposed to the ripple effect and how different SC designs can be compared according to their resilience to severe disruptions.

In their Chapter "Ripple Effect Analysis of a Two-Stage Supply Chain Using Probabilistic Graphical Model", Seyedmohsen Hosseini and MD Sarder develop a new methodology to control and monitor the ripple effect in SCs by analyzing the ripple effect in a two-stage SC. This probabilistic graphical model is capable of capturing disruption propagation that can transfer from upstream suppliers to downstream end customer in the SC.

Dmitry Ivanov's Chapter "Entropy-Based Analysis and Quantification of Supply Chain Recoverability" addresses the problem of designing resilient SCs at the semantic network level. The entropy method is used to show the interrelations between SC design and recoverability. Easy-to-compute quantitative measures are proposed to estimate SC recoverability. For the first time, an entropy-based SC analysis is brought into correspondence with consideration of SC structural recoverability and flexibility downstream in the SC. Exact and heuristic computation algorithms are suggested and illustrated. This approach and recoverability measure can be applied in selecting a resilient SC design according to potential recoverability.

In their Chapter "New Measures of Vulnerability within Supply Networks: A Comparison of Industries", James P. Minas, N.C. Simpson, and Ta-Wei (Daniel) Kao point out that one distinct element of SC risk is the potential for detrimental material to propagate through the SC undetected, eventually exposing unsuspecting consumers to defective products. Based on methods inspired by epidemiology, new measures for quantifying this risk are proposed. The authors apply these measures to real-life supply networks from eight industries to compare their relative levels of risk across a 17-year time horizon. The results indicate that while aggregate SC risk has increased over time, both the level and sources of risk differ markedly by industry.

Dmitry Ivanov and Maxim Rozhkov study capacity disruption and recovery policy impacts on SC performance in their Chapter "Disruption Tails and Revival Policies in the Supply Chain". A discrete-event simulation methodology is used for analysis with real company data and real disruptions. Two novel findings are presented. First, disruption-driven changes in SC behavior may result in backlog and delayed orders, the accumulation of which in the post-disruption period we call "disruption tails". The transition of these residues into the post-disruption period causes post-disruption SC instability, resulting in further delivery delays and non-recovery of SC performance. Second, a smooth transition from a contingency policy through a special "revival policy" to the normal operation mode enables partial mitigation of the negative effects of the disruption tails. These results suggest three managerial insights. First, contingency policies need to be applied during the disruption period to avoid disruption tails. Second, recovery policies need to be extended toward integrated consideration of both the disruption and the post-disruption periods. Third, revival policies need to be developed for the transition from the contingency to the disruption-free operation mode. A revival policy is intended to mitigate the negative impact of the disruption tails and stabilize SC control policies and performance. The experimental results suggest a revival policy should be included in an SC resilience framework if performance cannot be recovered fully after capacity recovery.

In their Chapter "Managing Disruptions and the Ripple Effect in Digital Supply Chains: Empirical Case Studies", Ajay Das, Simone Gottlieb, and Dmitry Ivanov analyze the impact of accelerating digitalization on SC risk management. Digital technologies, such as big data analytics, Industry 4.0 applications, additive manufacturing, blockchain, advanced tracking and tracing technologies, and enterprise resource planning software systems are considered. Empirical evidence on the interrelations between digital technologies and the risk of SC disruptions, as well as the influence of the one on the other, are analyzed based on the findings from the multiple case studies. These findings are comprised of the insights and managerial recommendations of experts from multiple industries. The empirical analysis is guided by hypotheses and a conceptual framework based on extant theory.

Rameshwar Dubey devotes his Chapter "Resilience and Agility: The Crucial Properties of Humanitarian Supply Chain" to theorizing and testing the impact of agility and resilience on humanitarian supply chain performance. Supply chain agility and resilience are explained based on the existing literature and further tested the theory using confirmatory factor analysis. The multivariate statistical analyses suggest that supply chain agility is an important property of pre-disaster performance, and supply chain resilience is an important property of the post-disaster performance.

The chapter "Digital Supply Chain Twins: Managing the Ripple Effect Resilience, and Disruption Risks by Data-Driven Optimization, Simulation, and Visibility" is written by Dmitry Ivanov, Alexandre Dolgui, Ajay Das, and Boris Sokolov. The impact of digital technology, Industry 4.0, blockchain, and data analytics on the ripple effect and disruption risk management in SCs is studied in this chapter. This chapter does not pretend to be encyclopedic, but rather seeks to advance the knowledge we have to further research on the relationship between digitalization and SC disruptions risks based on recent literature and case studies. It then presents an SC risk analytics framework and explains the concept of digital SC twins. It analyzes perspectives and future transformations that can be expected in the transition towards cyber-physical SCs. It shows how digital technologies and smart operations can help to integrate resilience and lean thinking into a *resileanness* framework for a "Low-Certainty-Need" (LCN) SC.

Ripple Effect in the Supply Chain: Definitions, Frameworks and Future Research Perspectives

Dmitry Ivanov, Alexandre Dolgui and Boris Sokolov

Abstract This chapter aims at delineating major features of the ripple effect and methodologies to mitigate the supply chain disruptions and recover in case of severe disruptions. It observes the reasons and mitigation strategies for the ripple effect in the supply chain 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. Two special directions are highlighted. The first direction is the supply chain risk analytics for disruption risks and the data-driven ripple effect control in supply chains. The second direction is the concept of low-certainty-need (LCN) supply chains.

1 Ripple Effect in the Supply Chain: Basic Definitions

1.1 Supply Chain Risks and Ripple Effect

Disruptions are considered high-impact-low-frequency events (e.g. fire or tsunami) in the supply chain (SC) that change the SCs structural design and significantly impact performance. The propagation of a disruption through an SC and its associated impact is called the *ripple effect*. A ripple effect is distinct from the well-known bullwhip

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D. Ivanov et al. (eds.), *Handbook of Ripple Effects in the Supply Chain*,
International Series in Operations Research & Management Science 276,
https://doi.org/10.1007/978-3-030-14302-2_1

effect. It manifests when the impact of an SC disruption cannot be localized or being contained to one part of the SC and cascades downstream, resulting in a high-impact effect on SC performance (Dolgui et al. 2018). The ripple effect considers structural network dynamics in the SC while bullwhip effect characterizes the oscillations in operational parameters. The ripple effect is initiated by a severe disruption and describes the propagation of this disruption downstream the SC, e.g. in terms of propagation of the demand fulfilment downscaling as a result of a severe disruption. In more severe cases, the ripple effect can be manifested in temporary switching off some nodes and arcs in the network, e.g. due to material shortage. The bullwhip effect, on the contrary, is launched by a small operational deviation and is expected to be amplified in the upstream direction.

While the reasons for bullwhip effect have been extensively studied over the past two decades, the ripple effect is quite a new phenomenon and analysis its impacts deserve more research attention. These impacts 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.

Consider an example. On 17 October 2016 as a result of an incorrect maintenance operation on a pipeline at BASF facility in Ludwigshafen (Germany), there was an explosion and subsequent fires at North Harbor, a terminal for the supply of raw materials such as naphtha, methanol and compressed liquefied gases. More than 2.6 million tons of goods are handled there each year and an average of seven ships a day moor at its docks. Two steam crackers, the starting point for producing basic chemicals, needed to be stopped because they could no longer be supplied, and 22 were only partially working. The two steam crackers could have been restarted two days later, but only in May 2017 was the concept for reconstruction released whereby the reconstruction should be completed by September 2017. Restricted production output, a daily revenue decrease of 10–15% as compared to the previous year during the disruption period, impact on the basic chemicals division (about 21% of sales), delivery delays, limited access to key raw materials, exhausted product inventories and a forecasted impact on 6% of BASFs annual earnings were some of the consequences of this incident (Dolgui et al. 2018, and references within). Logistics was temporarily shifted from ships and pipelines to trucks and trains. BASF was in close contact with its customers to keep them informed about the current availability of products to minimize the impact on customer deliveries. Because of BASF integrated “Verbundsystem” (networking system), comprised of various plants and delivery systems for feedstocks, the incident had an impact along the global SC. This high and long-term impact is the so-called ripple effect (Ivanov et al. 2014a, b).

BASF built a resilient SC, which is why the economic consequences of the aforementioned incident were considerably smaller than expected. BASF took process safety and risk prevention measures that included globally valid guidelines and requirements for buildings, etc. and practical security trainings for employees and support staff. Along with process safety and risk prevention measures, BASF has global emergency response management. This management consists of the integration of worldwide group companies, joint ventures, partners, suppliers and customers. Emergency phones and an integrated network of control centres (e.g. internal/external

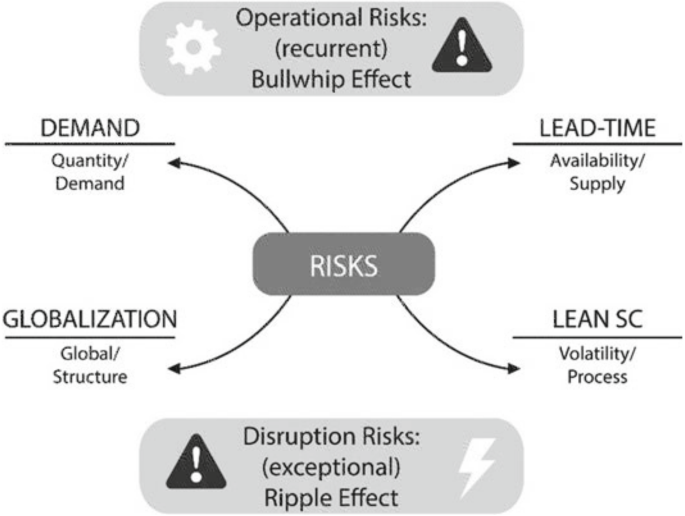

Fig. 1 Supply chain operational and disruption risks (Ivanov 2018b)

fire departments and rescue service) also enable this global emergency response management to work even more closely together. BASF was prepared for the incident in October 2016, but there is still long-term impact.

The BASF example shows the importance of SC risk management and the threats that severe disruptions may influence the SC performance. *Risk management* in the SC became one of the most important topics in research and practice over the last decade. A number of books (Handfield and McCormack 2008; Kouvelis et al. 2012; Waters 2011; Gurnani et al. 2012; Heckmann 2016; Mistree et al. 2017; Khojasteh 2017; Ivanov 2018b; Sawik 2018) and literature review papers (Klibi et al. 2010; Simangunsong et al. 2012; Ho et al. 2015; Fahimnia et al. 2015; Snyder et al. 2016; Dolgui et al. 2018) provide insightful overviews and introductions to different aspects of this exciting field.

Recent literature introduced different classifications of SC risks (Chopra and Sodhi 2004; Tang and Musa 2011; Ho et al. 2015; Quang and Hara 2018; Macdonald et al. 2018) (see Fig. 1).

Risks of demand and supply uncertainty are related to random uncertainty and business-as-usual situation. Such risks are also known as *recurrent* or *operational risks. SC* managers achieved significant improvements at managing global SCs and mitigating recurrent SC risks through improved planning and execution (Chopra and Sodhi 2014).

From 2000 thru 2018, SC disruptions (e.g. because of both natural and man-made disasters, such as on 11 March 2011 in Japan, floods in Thailand in 2011, fire in the Phillips Semiconductor plant in New Mexico, etc.) occurred in greater frequency and intensity, and thus with greater consequences (Chopra and Sodhi 2014; Simchi-Levi et al. 2014). Hendricks and Singhal (2005) quantified the negative

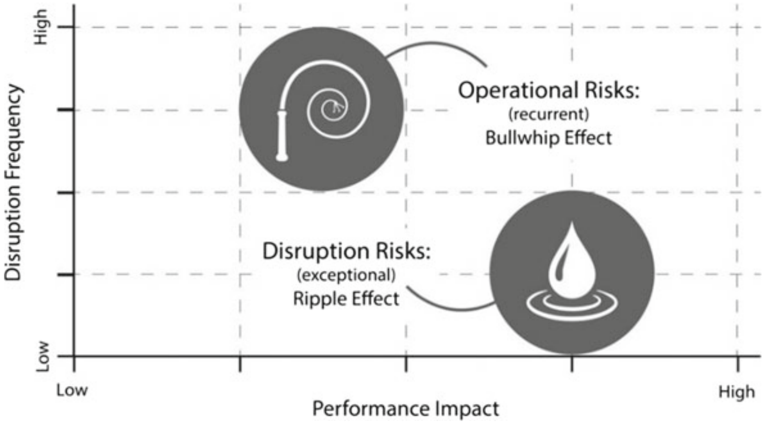

Fig. 2 Operational and disruption risks in supply chains (Ivanov et al. 2019)

effects of SC disruption through empirical analysis and found 33–40% lower stock returns relative to their benchmarks over a 3-year time period that started one year before and ended two years after a disruption.

1.2 Disruption Risks and the Ripple Effect

Disruption risks represent a new challenge for SC managers who face the *ripple effect* (Liberatore et al. 2012; Ivanov et al. 2014a, b; Levner and Ptuskin 2018; Ivanov 2018a; Dolgui et al. 2018; Ivanov and Dolgui 2018; Ivanov et al. 2018; Ivanov et al. 2019; Ivanov and Rozhkov 2017; Hosseini et al. 2019) subject to *structural disruptions* in the SC, unlike the *parametrical deviations* in the bullwhip effect (Fig. 2).

In the last two decades, considerable advancements have been achieved in research regarding the mitigation of inventory and production shortages and response to demand fluctuations. In particular, the *bullwhip effect* in the SC has been extensively considered in this domain subject to *randomness uncertainty* with the help of stochastic and simulation models.

The differences between the bullwhip effect and ripple effect are presented in Table 1 (Dolgui et al. 2018, 2019).

The Bullwhip effect considers weekly/daily demand and lead-time fluctuations as primary drivers of the changes in the supply chain which occur at the parametric level and can be eliminated in a short-term perspective. In recent years, the research community has started to investigate severe supply chain disruptions with long-term impacts that can be caused, for example, by natural disasters, political conflicts, terrorism, maritime piracy, economic crises, destroying of information systems, or transport infrastructure failures. We refer to these severe natural and man-made disasters as the ripple effect in the supply chain where changes in the supply chain

Table 1 Ripple effect and bullwhip effect (Dolgui et al. 2018)

Feature	Ripple effect	Bullwhip effect
What uncertainty?	Hazard, deep uncertainty	Random uncertainty
What risks?	Disruption, exceptional risks (e.g. a plant explosion)	Operational, recurrent risks (e.g. demand fluctuation)
What can be disturbed?	Structures and critical performance (such as supplier unavailability or revenue)	Operational parameters such as lead time and inventory
How are deviations prevented?	Proactive redundancy and flexibility	Information coordination
What happens after the disturbance?	Short-term stabilization and middle- and long-term recovery; high coordination efforts and investments	Short-term coordination to balance demand and supply
What is performance impact?	Output performance can decrease, such as in annual revenues or profits	Current performance can decrease such as in daily or weekly stock out/overage costs

occur at the structural level and recovery may take mid- and long-term periods of time with significant impact on output performance such as annual revenues. In this setting, supply chain disruption management can be considered a critical capability which helps to create cost-efficient supply chain protection and implement appropriate actions to recover supply chain disruptions and performance.

Most studies on supply chain disruption consider how changes to some variables are rippling through the rest of the supply chain and impacting performance. Studies by Ivanov et al. (2014a, b) and Dolgui et al. (2018) suggest considering this situation as *the ripple effect in the supply chain*, as an analogy to computer science, where the ripple effect determines the disruption-based scope of changes in the system.

The *ripple effect* in the supply chain occurs if a disruption cannot be localized and cascades downstream impacting supply chain performance such as sales, stock return, service level and costs (Ivanov et al. 2014a, 2015; Dolgui et al. 2018; Ivanov 2018a). The methodical elaborations on the evaluation and understanding of low-frequency-high-impact disruptions are therefore vital for understanding and further development of network-based supply concepts (Tomlin 2006; Liberatore et al. 2012; Sawik 2016).

Details of empirical or quantitative methodologies differ across the works on supply chain disruption management, but most share a basic set of attributes:

- a disruption (or a set of disruptions)
- impact of the disruption on operational and strategic economic performance
- stabilization and recovery policies.

Within this set of attributes, most studies on supply chain disruption consider how changes to some variables are rippling through the rest of the supply chain and

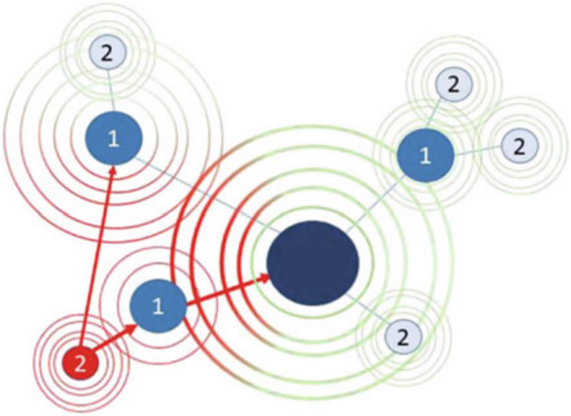

Fig. 3 Disruption propagation in the supply chain (Ivanov et al. 2019)

impacting performance. We suggest considering this situation, *the ripple effect in the supply chain*, as an analogy to computer science, where the ripple effect determines the disruption-based scope of changes in the system.

The ripple effect is a phenomenon of disruption propagations in the supply chain and their impact on output supply chain performance (e.g. sales, on time delivery and total profit). It may have more serious consequences than just short-term performance decrease. It can result in market share losses (e.g. Toyota lost its market leader position after tsunami in 2011 and needed to redesign supply chain coordination mechanism). The ripple effect is also known as “domino effect” or “snowball effect”. The reasons for ripple effect are not difficult to find. With increasing supply chain complexity and consequent pressure on speed and efficiency, an ever-increasing number of industries come to be distributed worldwide and concentrated in industrial districts. In addition, globalized supply chains depend heavily on permanent transportation infrastructure availability.

The ripple effect describes disruption propagation in the supply chain, impact of a disruption on supply chain performance and disruption-based scope of changes in supply chain structures and parameters.

Following a disruption, its effect ripples through the supply chain. The missing capacities or inventory at the disrupted facility may cause missing materials and production decrease at the next stages in the supply chain. Should the supply chain remain in the disruption model longer than some critical period of time (i.e. *time-to-survive* (Simchi-Levi et al. 2015)), critical performance indicators such as sales or stock returns may be affected.

Ripple effects are not an infrequent occurrence. In many examples, supply chain disruptions go beyond the disrupted stage; i.e. the original disruption causes disruption propagation in the supply chain, at times still higher consequences are caused (Fig. 3).

The studies by Liberatore et al. (2012), Ivanov et al. (2014a, b, 2016, 2017b), Han and Shin (2016), Sokolov et al. (2016), Mizgier (2017), Schmitt et al. (2017), Ivanov

Table 2 Ripple effect reasons and countermeasures (based on Dolgui et al. 2018)

Reason	SCM impact	Ripple effect impact	Countermeasures
Leanness	Single sourcing	In the non-disrupted scenario, it is irrational to avoid lean practices. At the same time, a capacity disruption may result in the ripple effect and performance decrease. Recommendation to use capacity buffers or a backup facility as additional capacity reserves	Multiple/dual sourcing/backup suppliers
	Low inventory		Risk mitigation inventory
	Inflexible capacity		Postponement
Complexity	Globalization	Without a coordinated contingency policy, disruption recovery and performance impact estimation can be very long lasting and expensive. Coordinated control algorithms are needed to monitor SC behaviour, identify disruptions and adjust order allocation rules using a coordinated contingency policy	Geographical sourcing diversification
	Decentralization		Global SC contingency plans
	Multistage SCs		Supplier segmentation according to disruption risks

(2017, 2018b), Levner and Ptuskin (2018), Dolgui et al. (2018), Pavlov et al. (2018), Scheibe and Blackhurst (2018), Akkermans and van Wassenhove (2018) extensively analysed SC ripple effect, its reasons and efficient countermeasures. These findings are summarized in Table 2.

First, literature provides evidence that disruption duration and propagation impact SC performance. Second, proactive strategies such as backup facilities and inventory have positive impacts concerning both performance and prevention of disruption propagation. Third, the speed of recovery plays an important role in mitigating the performance impact of disruptions. Fourth, an increase in SC resilience implies significant cost increases in the SC.

1.3 Ripple Effect and Supply Chain Structural Dynamics

Ripple effect causes structural changes in the SC. The main supply chain features are the multiple structure design and changeability of structural parameters because of objective and subjective factors at different stages of the supply chain life cycle. In other words, supply chain *structural dynamics* is constantly encountered in practice

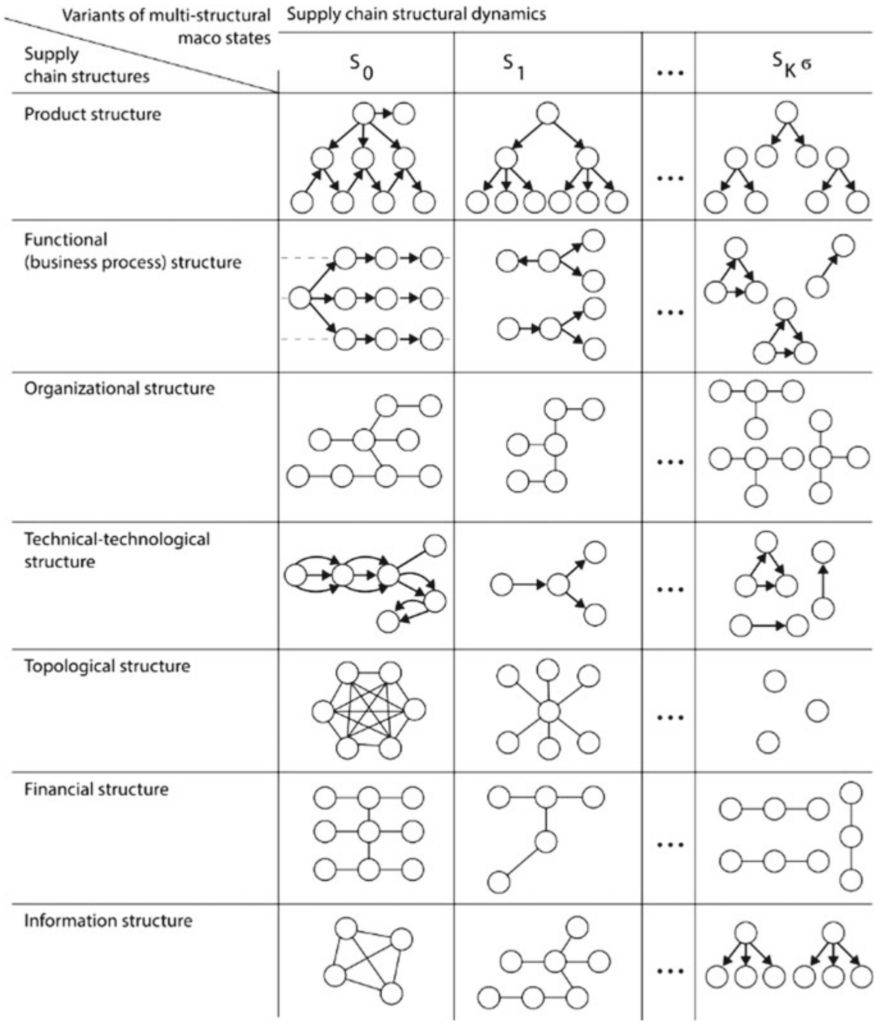

Fig. 4 Supply chain multi-structural composition and structural dynamics (based on Ivanov et al. 2010)

(Ivanov and Sokolov 2010; Ivanov et al. 2010). Figure 4 depicts major structures and their changes in dynamics. The composition of different structures at different point in time results in supply chain multi-structural macrostates *S*. Multi-structural macrostates describe supply chain design evolution over time due to planned (controllable) and uncertain factors.

The multi-dimensional dynamic space along with coordinated and distributed decision-making guides us in understanding modern supply chains as *multi-structural dynamic systems* (Ivanov et al. 2010).

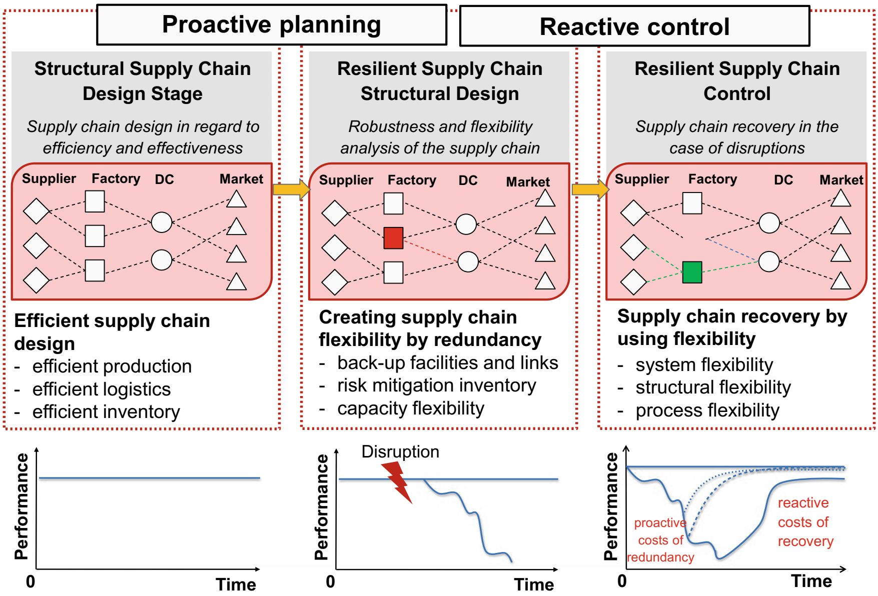

Fig. 5 Supply chain structural dynamics control (Ivanov 2018b)

1.4 *Supply Chain Performance, Resilience and Ripple Effect Control*

One of the main objectives of supply chain management is to increase total supply chain performance, which is basically referred to as supply chain effectiveness (i.e. sales and service level) and efficiency (supply chain costs). At the same time, the achievement of planned performance can involve the impact of disruptions in a real-time execution environment. Supply chain 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 supply chain 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 behaviour in the case of disturbances in order to achieve planned performance using recovery actions.

Decisions in supply chain structural dynamics control can be roughly classified into proactive and reactive stages (Fig. 5).

Resilient supply chain design extends traditional supply chain design approaches with regard to the incorporation of redundancies such as backup 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

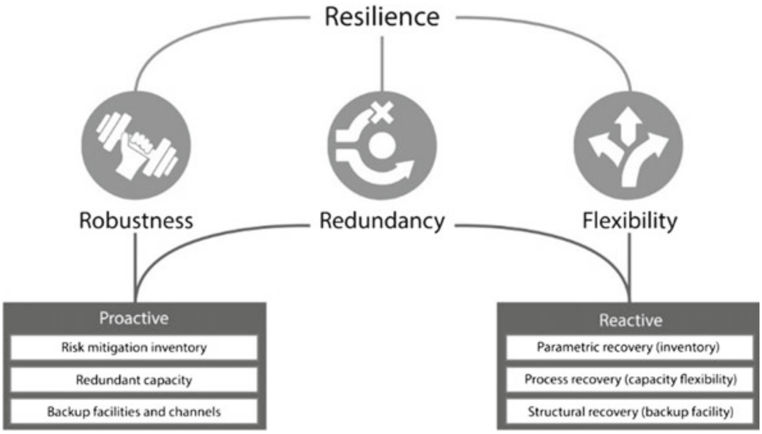

Fig. 6 Resilience control elements (Ivanov 2018b)

in supply chain structures in order to recover system performance and operational processes.

In Fig. 6, we summarize relations of redundancy, robustness, resilience and flexibility (see also Ivanov and Sokolov 2013 and Ivanov 2018b).

There is a strong and growing literature on robustness and resilience as two fundamental concepts to analyse SC performance with severe uncertainty consideration and with regards to scattered disruptive events resulting in SC structural dynamics. An SC is called *robust* if it is able to absorb disturbances and continue execution with minimal impact on performance. The performance of such an SC is insensitive to the negative impacts of disruptions (Ivanov and Sokolov 2013; Han and Shin 2016). 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*. 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. 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.

In Fig. 7, we summarize the relationships between redundancy, robustness, flexibility and resilience.

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, Wang and Zhang 2018), disruption risks and their propagation in the SC are mainly caused by single sourcing, low risk mitigation inventory, overutilization of capacities, low-level safety technologies and missing contingency plans.