Springer Series in Supply Chain Management

Alexandre Dolgui
Dmitry Ivanov
Boris Sokolov *Editors*

Supply Network Dynamics and Control

Springer

Springer Series in Supply Chain Management

Volume 20

Series Editor
Christopher S. Tang, University of California, Los Angeles, CA, USA

Supply Chain Management (SCM), long an integral part of Operations Management, focuses on all elements of creating a product or service, and delivering that product or service, at the optimal cost and within an optimal timeframe. It spans the movement and storage of raw materials, work-in-process inventory, and finished goods from point of origin to point of consumption. To facilitate physical flows in a time-efficient and cost-effective manner, the scope of SCM includes technology-enabled information flows and financial flows.

The Springer Series in Supply Chain Management, under the guidance of founding Series Editor Christopher S. Tang, covers research of either theoretical or empirical nature, in both authored and edited volumes from leading scholars and practitioners in the field – with a specific focus on topics within the scope of SCM.

This series has been accepted by Scopus.

Springer and the Series Editor welcome book ideas from authors. Potential authors who wish to submit a book proposal should contact Ms. Jialin Yan, Associate Editor, Springer (Germany), e-mail: jialin.yan@springernature.com

Alexandre Dolgui • Dmitry Ivanov • Boris Sokolov
Editors

Supply Network Dynamics and Control

Springer

Editors
Alexandre Dolgui
Department of Automation, Production and Computer Sciences
IMT Atlantique, LS2N-CNRS
Nantes, France

Dmitry Ivanov
Department of Business and Economics, Supply Chain and Operations Management
Berlin School of Economics and Law
Berlin, Germany

Boris Sokolov
Laboratory for Information Technologies in Systems Analysis and Modeling
St. Petersburg Institute of Informatics and Automation of the RAS (SPIIRAS)
St. Petersburg, Russia

ISSN 2365-6395 ISSN 2365-6409 (electronic)
Springer Series in Supply Chain Management
ISBN 978-3-031-09178-0 ISBN 978-3-031-09179-7 (eBook)
https://doi.org/10.1007/978-3-031-09179-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Chapter 1
Introduction to Supply Network Dynamics and Control

Alexandre Dolgui, Dmitry Ivanov, and Boris Sokolov

Abstract Supply chain networks undergo transformations on the scale unlike any seen before. Extensive technology adoptions in supply chain networks render changes in network structures entailing multi-structural dynamics (i.e., new technologies such as Industry 4.0 and additive manufacturing lead to creating more dynamic and *reconfigurable* supply chains). This chapter presents an introduction to the book on supply network dynamics and control with chapters devoted to theory, methods, and applications in manufacturing, service, supply chain, and Industry 4.0 systems.

Keywords Supply chain · Dynamics · Control · Industry 4.0 · Cloud supply chain · Digital twin · Reconfigurable supply chain

Supply chain networks undergo transformations on the scale unlike any seen before. Extensive technology adoptions in supply chain networks render changes in network structures entailing multi-structural dynamics (i.e., new technologies such as Industry 4.0 and additive manufacturing lead to creating more dynamic and *reconfigurable* supply chains). Technologies also allow for better observing and controlling supply chain dynamics (e.g., through visibility and real-time data

---

A. Dolgui
Department of Automation, Production and Computer Sciences, IMT Atlantique, LS2N – CNRS UMR 6004 La Chantrerie, Nantes, France
e-mail: alexandre.dolgui@imt-atlantique.fr;
URL: https://www.imtatlantique.fr/en/person/alexandre-dolgui

D. Ivanov (✉)
Supply Chain and Operations Management, Berlin School of Economics and Law, Berlin, Germany
e-mail: divanov@hwr-berlin.de; URL: https://blog.hwr-berlin.de/ivanov

B. Sokolov
Laboratory for Information Technologies in Systems Analysis and Modeling, St. Petersburg Institute of Informatics and Automation of the RAS (SPIIRAS), St. Petersburg, Russia
e-mail: sokol@iias.spb.su; URL: http://litsam.ru/index.php/en/staff-en/boris-v-sokolov

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_1

analytics). On the other hand, the COVID-19 pandemic has strengthened the disruption-related questions of supply chain network dynamics and clearly showed the key role of dynamics control, adaptability, and *viability* in supply chain networks both at the strategic and operational levels.

Overall, modern and future supply chain networks are increasingly challenged by uncertainty and risks, multiple feedback cycles, adaptive mechanisms, and dynamics. Supply network control is multi-faceted area and can be seen in many ways, such as structural dynamics, feedback mechanisms, adaptation loops, multi-period control of material flows, and operational dynamics (i.e., inventory dynamics). Supply network dynamics has been studied by various methodologies such as optimal control, model-predictive control adaptive control, feedback control, ecological modelling, chaos theory, complex adaptive systems, differential dynamic games, systems dynamics, complex adaptive system to name just a few.

Empirical problem settings, modelling approaches, mathematical techniques differ across these methodologies but most of them share a common set of attributes: system evolution over time, dynamic changes in the system, and changes in system behaviors through interactions with the environment. As such, different control and dynamical system theories have commonalities in taking into account the dynamics, non-linearity, and non-stationary of supply network processes.

This book offers an introduction and advanced techniques to supply network dynamics with applications to manufacturing, service, supply chain, and Industry 4.0 systems for larger audience. In particular, the methods of optimal control, model-predictive control adaptive control, feedback control, ecological modelling, chaos theory, complex adaptive systems, network and complexity theory, differential dynamic games, systems dynamics (but not limited to) are in the scope of this book. We also encourage empirical research chapters which theorize supply network dynamics and control paradigms.

This book is intended to cover the area of SC dynamics and control at three levels:

- SC network dynamics analysis (e.g., structural dynamics)
- SC design and planning dynamics (e.g., material flow reconfiguration)
- SC operational dynamics (e.g., inventory dynamics)

The variety of quantitative analysis methodologies, optimization, simulation, optimal control, model-predictive control adaptive control, feedback control, ecological modelling, chaos theory, complex adaptive systems, differential dynamic games, systems dynamics, Bayesian networks, and analytics-driven approaches are welcome. We also encourage empirical research chapters which theorize supply network dynamics and control paradigms.

The purpose of this book is to comprehensively present recent developments in supply network dynamics research and to systemize these developments in new taxonomies and methodological principles. This book addresses the needs of both researchers and practitioners to uncover the challenges and opportunities of supply chain and operations management by dynamic system analysis. We present research done with the help of different methodologies to show the commonalities, differences, and application areas of different methods to study supply network dynamics.

The book provides both a state-of-the-art progress and looks at new topics for supply network dynamics such as *Industry 4.0, Viable Supply Chain, Reconfigurable Supply Chain, digital twins, sustainability, cloud manufacturing, ripple effect, and resilience*, to name a few. For the first time, we present a book that collates recent research on control and dynamical system applications to supply chain and operations management. Those application areas include but are not limited to scheduling, production and inventory control, stability, and resilience analysis. Control and dynamical systems allow addressing conveniently some fundamental properties of supply chains, manufacturing, and logistics systems, such as non-linearities, information feedbacks, time-related issues, and adaptation, which might be difficult to model in other methods.

Distinctive Features of the Book:

- It uncovers fundamental principles and recent developments in control and dynamical system theories with applications to supply chains, manufacturing, and logistics systems.
- Bridging the fundamentals of control and dynamical system theories to supply chain and operations management.
- Systemizing new developments and deciphering taxonomies and methodological principles to shape the research domain of supply network dynamics control.
- Innovative applications of uncertainty modellings in supply chains, manufacturing, and logistics systems.
- Unique multi-disciplinary view with utilization of control engineering, operations research, industrial engineering and computer science techniques.

Graduate and PhD students in industrial engineering, operations research and management science, production engineers, supply chain and operations management professionals, operations and supply chain researchers will benefit from a variety of chapters written by the leading researchers from different continents.

Dimitris Mourtzis and Nikos Panopoulos review in their chapter "*Digital Transformation Process Towards Resilient Production Systems and Networks*" recent advances in adoption of Industry 4.0 technologies towards accelerating the digital transformation of global production networks. They present a framework for digital transformation and business model change in Small Medium Enterprises (SMEs) during disruption (i.e., pandemic). The chapter explains how digital technology can help to build digital, resilient, and cloud-based SC networks.

Win P. V. Nguyen, Puwadol Oak Dusadeerungsikul, and Shimon Y. Nof describe in their chapter "*Collaborative Control, Task Administration, and Fault Tolerance for Supply Chain Network-Dynamics*" how the dynamic requirements and behaviors of SC networks and their associated complex challenges can be and have been addressed by the tools and protocols of the collaborative control theory. These tools and protocols have been developed, tested, and implemented by the PRISM Center at Purdue University and by other researchers and industries around the world. The authors stress that collaborative control and collaboration engineering are important for the successful coordination of supply activities and interactions, due to the multiple parties involved in the supply processes and services, all subjected to disruption, errors, conflicts, and dynamic many changes. The chapter offers an overview of key relevant research, methods, and tools and illustrates case studies of successful implementation.

Melanie Kessler and Julia C. Arlinghaus elaborate in their chapter "*Managing supply chain disruption by collaborative resource sharing*" on an empirical evidence for the value of collaboration in SC resilience. Based on a survey of 216 SC risk managers of European production firms, this chapter introduces the collaborative sharing of production and human resources as a method to recover from disruptions. Trust and commitment are identified as the core values for the collaborative resource sharing to increase SC resilience. The authors propose a framework to explicate the main drivers for collaborative human resource and production sharing and offer first practical recommendations for SC risk managers to support the process of the development of mitigation strategies to recover from SC disruptions.

Towfique Rahman and Sanjoy Kumar Paul devote their chapter "*Reconfigurable strategies to manage uncertainties in supply chains due to large-scale disruptions*" to understanding of the uncertainties in SC encountered in the wake of large-scale disruptions. They offer implications of reconfigurable strategies to manage uncertainties in SCs due to large-scale disruption. The authors conclude that adoption of reconfigurable strategies to mitigate unknown-unknown uncertainties caused by large-scale disruptions is important to make the supply chains viable.

Mirco Peron, Fabio Sgarbossa, Dmitry Ivanov, and Alexandre Dolgui show in their chapter "*Impact of Additive Manufacturing on Supply Chain resilience during COVID-19 pandemic*" how simulation can help analyzing the value of additive manufacturing in the setting of a super disruption on the COVID-19 pandemic example. Using anyLogistix SC software, they define and test several pandemic scenarios unveiling the impact of additive manufacturing usage on SC performance. They generalize experimental results and deduce some general conclusions suggesting how SC managers can beneficially use additive manufacturing in a pandemic setting.

Jebum Pyun, Seayoung (Samantha) Park, and Jiho Yoon introduce in their chapter "*Short-term Routing Models for COVID-19 Treatment Transfer between Hospitals*" an optimization model for reactive short-term vehicle routings for such transfers. The optimization model can simultaneously grasp vehicle movement and cargo location information while minimizing the total travel time of vehicles, which can handle the urgency of treatment transfers by changing the value of the limited travel time of vehicles. Although the model does not include every condition that can be considered in the treatment transfers between hospitals, it shows the potential of the model proposed in the transfer of treatment in case of shortages.

Fazel Ansari and Linus Kohl provide in their chapter "*AI-enhanced Maintenance for Building Resilience and Viability in Supply Chains*" an AI (artificial intelligence)-enhanced approach for integrative modelling and analysis of SC Key Performance Indicators (KPIs) towards building resilience and viability in manufacturing and supply chains, aided by Dynamic Bayesian Networks (DBN). They show how utilizing predictive analytics and semantic modelling may improve target performance metrics, increases flexibility, and enables the development of a resilient and viable SC.

Arvid Holzwarth, Cornelia Staib, and Dmitry Ivanov develop in their chapter "*Building viable digital business ecosystems with collaborative supply chain platform SupplyOn*" a practical view on digital SCs that evolve towards business ecosystems becoming ever more complex and in which companies and SC collaborate in an increasingly networked manner. They show how viability consideration at the level of ecosystems can be supported by associated digital collaborative SC platforms. To illustrate, a concrete use case is highlighted at the Chinese premium car manufacturer Seres, where the Supplier Collaboration Portal SupplyOn with its integrated solutions has made a significant contribution to building ecosystem viability.

References

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.

Aldrighetti, R., Battini, D., Ivanov, D., & Zennaro, I. (2021). Costs of resilience and disruptions in supply chain network design models: A review and future research directions. *International Journal of Production Economics, 235*, 108103.

Axsäter, S. (1985). Control theory concepts in production and inventory control. *International Journal of Systems Science, 16*(2), 161–169.

Axsäter, S., & Rosling, K. (1993). Installation vs. echelon stock policies for multi-level inventory control. *Management Science, 39*, 1274–1280.

Azadegan, A., Mellat Parast, M., Lucianetti, L., Nishant, R., & Blackhurst, J. (2020). Supply chain disruptions and business continuity: An empirical assessment. *Decision Sciences, 51*(1), 38–73.

Basole, R. C., & Bellamy, M. A. (2014). Supply network structure, visibility, and risk diffusion: A computational approach. *Decision Sciences, 45*(4), 1–49.

Bensoussan, A., Çakanyildirim, M., & Sethi, S. (2007). Optimal ordering policies for inventory problems with dynamic information delays. *Production and Operations Management, 16*(2), 241–256.

Bode, C., Wagner, S. M., Petersen, K. J., & Ellram, L. M. (2011). Understanding responses to supply chain disruptions: Insights from information processing and resource dependence perspectives. *Academy of Management Journal, 54*(4), 833–856.

Braun, M. W., Rivera, D. E., Flores, M. E., Carlyle, W. M., & Kempf, K. G. (2003). A model predictive control framework for robust management of multi-product, multi-echelon demand networks. *Annual Reviews in Control, 27*, 229–245.

Brintrup, A., Wang, Y., & Tiwari, A. (2015). Supply networks as complex systems: A network science-based characterization. *IEEE Systems Journal, 99*, 1–12.

Brintrup, A., Chauhan, V., & Perera, S. (2021). The relationship between nested patterns and the ripple effect in complex supply networks. *International Journal of Production Research, 59*(1), 325–341.

Choi, T. Y., Dooley, K. J., & Rungtusanatham, M. (2001). Supply networks and complex adaptive systems: Control versus emergence. *Journal of Operations Management, 19*(3), 351–366.

Choi, T.-M. (2021). Facing market disruptions: Values of elastic logistics in service supply chains. *International Journal of Production Research, 59*(1), 286–300.

Choi, T.-M. (2018). A system of systems approach for global supply chain management in the big data era. *IEEE Engineering Management Review, 46*(1), 91–97.

Craighead, C. W., Ketchen, D. J., & Darby, J. L. (2020). Pandemics and supply chain management research: Toward a theoretical toolbox. *Decision Sciences, 51*(4), 838–866.

Dejonckheere, J., Disney, S. M., Lambrecht, M. R., & Towill, D. R. (2004). The impact of information enrichment on the bullwhip effect in supply chains: A control engineering perspective. *European Journal of Operational Research, 153*(3), 727–750.

Demirel, G., MacCarthy, B. L., Ritterskamp, D., Champneys, A., & Gross, T. (2019). Identifying dynamical instabilities in supply networks using generalized modeling. *Journal of Operations Management, 65*(2), 133–159.

Disney, S. M., Towill, D. R., & Warburton, R. D. H. (2006). On the equivalence of control theoretic, differential, and difference equation approaches to modeling supply chains. *International Journal of Production Economics, 101*, 194–208.

Disney, S. M., & Towill, D. R. (2002). A discrete transfer function model to determine the dynamic stability of a vendor managed inventory supply chain. *International Journal of Production Research, 40*, 179–204.

Dolgui, A., Ivanov, D., Sethi, S. P., & Sokolov, B. (2019). Scheduling in production, supply chain and Industry 4.0 systems by optimal control. *International Journal of Production Research, 57*(2), 411–432.

Dolgui, A., Ivanov, D., Potryasaev, S., Sokolov, B., Ivanova, M., & Werner, F. (2020a). Blockchain-oriented dynamic modelling of smart contract design and execution control in the supply chain. *International Journal of Production Research, 58*(7), 2184–2199.

Dolgui, A., Ivanov, D., & Sokolov, B. (2020b). Reconfigurable supply chain: The X-Network. *International Journal of Production Research, 58*(13), 4138–4163.

Dolgui, A., & Ivanov, D. (2020). Exploring supply chain structural dynamics: New disruptive technologies and disruption risks. *International Journal of Production Economics, 229*, 107886.

Dolgui, A., & Ivanov, D. (2022). 5G in digital supply chain and operations management: Fostering flexibility, end-to-end connectivity and real-time visibility through internet-of-everything. *International Journal of Production Research, 60*(2), 442–451.

Dubey, R., Gunasekaran, A., Childe, S. J., Wamba, S. F., Roubaud, D., & Foropon, C. (2021). Empirical investigation of data analytics capability and organizational flexibility as complements to supply chain resilience. *International Journal of Production Research, 59*(1), 110–128.

El Baz, J., & Ruel, S. (2021). Can supply chain risk management practices mitigate the disruption impacts on supply chains' resilience and robustness? Evidence from an empirical survey in a COVID-19 outbreak era. *International Journal of Production Economics, 233*, 107972.

Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., & Strandhagen, J. O. (2022). Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Annals of Operations Research, 308*, 125–143.

Fraccascia, L., Giannoccaro, I., & Albino, V. (2017). Rethinking resilience in industrial symbiosis: Conceptualization and measurements. *Ecological Economics, 137*, 148–162.

Frazzon, E. M., Kück, M., & Freitag, M. (2018). Data-driven production control for complex and dynamic manufacturing systems. *CIRP Annals*. https://doi.org/10.1016/j.cirp.2018.04.033

Fu, D., Ionescu, C. M., & Aghezzaf, E. H. (2015). Quantifying and mitigating the bullwhip effect in a benchmark supply chain system by an extended prediction self-adaptive control ordering policy. *Computers and Industrial Engineering, 81*, 46–57.

Gao, S., & Chen, W. (2017). Efficient feasibility determination with multiple performance measure constraints. *IEEE Transactions on Automatic Control, 62*(1), 113–122.

Garcia, C. A., Ibeas, A., Herrera, J., & Vilanova, R. (2012). Inventory control for the supply chain: An adaptive control approach based on the identification of the lead-time. *Omega, 40*(3), 314–327.

Gershwin, S. B. (2018). The future of manufacturing systems engineering. *International Journal of Production Research, 56*(1–2), 224–237.

Ghadge, A., Er, M., Ivanov, D., & Chaudhuri, A. (2021). Visualisation of ripple effect in supply chains under long-term, simultaneous disruptions: A System Dynamics approach. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2021.1987547

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 Sciences, 49*(4), 625–659.

Giglio, D. (2015). Optimal control strategies for single-machine family scheduling with sequence-dependent batch setup and controllable processing times. *Journal of Scheduling, 18*(5), 525–543.

Gross, T., MacCarthy, B., & Wildgoose, N. (2018). Introduction to dynamics of manufacturing supply networks. *Chaos, 28*(9), 093111.

Hartl, R. F., Sethi, S. P., & Vickson, R. (1995). A survey of the maximum principle for optimal control problems with state constraints. *SIAM Review, 37*(2), 181–218.

He, X., Prasad, A., Sethi, S. P., & Gutierrez, G. J. (2007). A survey of Stackelberg differential game models in supply and marketing channels. *Journal of Systems Science and Systems Engineering, 16*(4), 385–413.

Hoberg, K., Bradley, J. R., & Thonemann, U. W. (2007). Analyzing the effect of the inventory policy on order and inventory variability with linear control theory. *European Journal of Operational Research, 176*(3), 1620–1642.

Hosseini, S., Ivanov, D., & Blackhurst, J. (2020). Conceptualization and measurement of supply chain resilience in an open-system context. *IEEE Transactions on Engineering Management*. https://doi.org/10.1109/TEM.2020.3026465

Hosseini, S., & Ivanov, D. (2020). Bayesian networks for supply chain risk, resilience and ripple effect analysis: A literature review. *Expert Systems with Applications, 161*, 113649.

Ivanov, D. (2021a). Supply chain viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. *International Journal of Production Research, 59*(12), 3535–3552.

Ivanov, D. (2021b). Lean resilience: AURA (Active Usage of Resilience Assets) framework for post-COVID-19 supply chain management. *International Journal of Logistics Management*. https://doi.org/10.1108/IJLM-11-2020-0448

Ivanov, D. (2022). Blackout and supply chains: Performance, resilience and viability impact analysis. *Annals of Operations Research*. https://doi.org/10.1007/s10479-022-04754-9.

Ivanov, D., Blackhurst, J., & Das, A., (2021). Supply Chain Resilience and its Interplay with Digital Technologies: Making innovations work in emergency situations. *International Journal of Physical Distribution & Logistics Management, 51*(2), 97–103.

Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "supply chain-as-a-service". *Transportation Research – Part E: Logistics and Transportation Review, 160*, 102676.

Ivanov, D., Sokolov, B., Chen, W., Dolgui, A., Werner, F., & Potryasaev, S. (2021). A control approach to scheduling flexibly configurable jobs with dynamic structural-logical constraints. *IISE Transactions, 53*(1), 21–38.

Ivanov, D. (2020a). Viable Supply Chain Model: Integrating agility, resilience and sustainability perspectives – lessons from and thinking beyond the COVID-19 pandemic. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03640-6

Ivanov, D. (2020b). Predicting the impact of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research – Part E, 136*, 101922.

Ivanov, D., & Sokolov, B. (2020). Simultaneous structural-operational control of supply chain dynamics and resilience. *Annals of Operations Research, 283*(1), 1191–1210.

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research, 58*(10), 2904–2915.

Ivanov, D., & Sokolov, B. (2013). 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.

Ivanov, D., Dolgui, A., & Sokolov, B. (2016c). Robust dynamic schedule coordination control in the supply chain. *Computers and Industrial Engineering, 94*(1), 18–31.

Ivanov, D., Mason, S., & Hartl, R. (2016b). Supply chain dynamics, control and disruption management. *International Journal of Production Research, 54*(1), 1–7.

Ivanov, D., & Sokolov, B. (2019). Simultaneous structural-operational control of supply chain dynamics and resilience. *Annals of Operations Research, 283*(1), 1191–1210.

Ivanov, D., Sethi, S., Dolgui, A., & Sokolov, B. (2018). A survey on the control theory applications to operational systems, supply chain management and Industry 4.0. *Annual Reviews in Control, 46*, 134–147.

Ivanov, D., Sokolov, B., & Kaeschel, J. (2010). A multi-structural framework for adaptive supply chain planning and operations control with structure dynamics considerations. *European Journal of Operational Research, 200*(2), 409–420.

Ivanov, D., Sokolov, B., & Dolgui, A. (2014). 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., Dolgui, A., Werner, F., & Ivanova, M. (2016a). A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory Industry 4.0. *International Journal of Production Research, 54*(2), 386–402.

Ivanov, D., & Rozhkov, M. (2020). 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, 291*(1–2), 387–407.

Ivanov, D., Dolgui, A., & Sokolov, B. (Eds.). (2019). *Handbook of Ripple effects in the supply chain*. Springer, ISBN 978-3-030-14301-5.

Ivanov, D. (2018). *Structural dynamics and resilience in supply chain risk management*. Springer, ISBN 978-3-319-69304-0.

Khmelnitsky, E., Presman, E., & Sethi, S. P. (2011). Optimal production control of a failure-prone machine. *Annals of Operations Research, 182*, 67–86.

Lanza, G., Ferdows, K., Kara, S., Mourtzis, D., Schuh, G., Váncza, J., … Wiendahl, H. P. (2019). Global production networks: Design and operation. *CIRP Annals, 68*(2), 823–841. https://doi.org/10.1016/j.cirp.2019.05.008

Li, Y., Chen, K., Collignon, S., & Ivanov, D. (2021). Ripple effect in the supply chain network: Forward and backward disruption propagation, network health and firm vulnerability. *European Journal of Operational Research, 291*(3), 1117–1131.

Lin, J., Spiegler, V., & Naim, M. (2018). Dynamic analysis and design of a semiconductor supply chain: A control engineering approach. *International Journal of Production Research, 56*(13), 4585–4611.

MacCarthy, B. L., Blome, C., Olhager, J., Srai, J. S., & Zhao, X. (2016). Supply chain evolution – theory, concepts and science. *International Journal of Operations & Production Management, 36*(12), 1696–1718.

MacCarthy, B., & Ivanov, D. (2022). *Digital supply chain*. Elsevier.

Mourtzis, D. (2022). The mass personalization of global networks. In *Design and operation of production networks for mass personalization in the era of cloud technology* (pp. 79–116). Elsevier. https://doi.org/10.1016/B978-0-12-823657-4.00006-3

Mourtzis, D., Panopoulos, N., & Angelopoulos, J. (2022). Production management guided by industrial internet of things and adaptive scheduling in smart factories. In *Design and operation of production networks for mass personalization in the era of cloud technology* (pp. 117–152). Elsevier. https://doi.org/10.1016/B978-0-12-823657-4.00014-2

Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2021). Robust engineering for the design of resilient manufacturing systems. *Applied Sciences, 11*(7), 3067. https://doi.org/10.3390/app11073067

Mourtzis, D. (2020). Simulation in the design and operation of manufacturing systems: State of the art and new trends. *International Journal of Production Research, 58*(7), 1927–1949. https://doi.org/10.1080/00207543.2019.1636321

Mourtzis, D. (2018). Design of customised products and manufacturing networks: Towards frugal innovation. *International Journal of Computer Integrated Manufacturing, 31*(12), 1161–1173. https://doi.org/10.1080/0951192X.2018.1509131

Mourtzis, D., Doukas, M., & Psarommatis, F. (2012). A multi-criteria evaluation of centralized and decentralized production networks in a highly customer-driven environment. *CIRP Annals, 61*(1), 427–430. https://doi.org/10.1016/j.cirp.2012.03.035

Nair, A., & Reed-Tsochas, F. (2019). Revisiting the complex adaptive systems paradigm: Leading perspectives for researching operations and supply chain management issues. *Journal of Operations Management, 65*(2), 80–92.

Nguyen, W. P. V., & Nof, S. Y. (2017). Collaborative response to disruption propagation (CRDP) in cyber-physical systems and complex networks. *Decision Support Systems, 117*, 1–13.

Nof, S. Y., Morel, G., Monostori, L., Molina, A., & Filip, F. (2006). From plant and logistics control to multi-enterprise collaboration. *Annual Reviews in Control, 30*(1), 55–68.

Ortega, M., & Lin, L. (2004). Control theory applications to the production-inventory problem: A review. *International Journal of Production Research, 42*, 2303–2322.

Paul, S. K., & Chowdhury, P. (2021). A production recovery plan in manufacturing supply chains for a high-demand item during COVID-19. *International Journal of Physical Distribution & Logistics Management, 51*(2), 104–125.

Pavlov, A., Ivanov, D., Werner, F., Dolgui, A., & Sokolov, B. (2020). Integrated detection of disruption scenarios, the ripple effect dispersal and recovery paths in supply chains. *Annals of Operations Research*. https://doi.org/10.1007/s10479-019-03454-1

Perea, E., Grossmann, I., Ydstie, E., & Tahmassebi, T. (2000). Dynamic modeling and classical control theory for supply chain management. *Computers and Chemical Engineering, 24*, 1143–1149.

Ponte, B., Wang, X., de la Fuente, D., & Disney, S. M. (2017). Exploring nonlinear supply chains: The dynamics of capacity constraints. *International Journal of Production Research, 55*(14), 4053–4067.

Puigjaner, L., & Lainez, J. M. (2008). Capturing dynamics in integrated supply chain management. *Computers & Chemical Engineering, 32*, 2582–2605.

Rozhkov, M., Ivanov, D., Blackhurst, J., & Nair, A. (2022). Adapting supply chain operations in anticipation of and during the COVID-19 pandemic. *Omega, 110*, 102635.

Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso, W. S. (2020). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03685-7

Sarimveis, H., Patrinos, P., Tarantilis, C. D., & Kiranoudis, C. T. (2008). Dynamic modeling and control of supply chain systems: A review. *Computers & Operations Research, 35*, 3530–3561.

Sawik, T. (2020). *Supply chain disruption management* (2nd ed.). Springer.

Schwartz, J. D., & Rivera, D. E. (2010). A process control approach to tactical inventory management in production-inventory systems. *International Journal of Production Economics, 125*(1), 111–124.

Sethi, S. P., Yan, H., Zhang, H., & Zhang, Q. (2002). Optimal and hierarchical controls in dynamic stochastic manufacturing systems: A survey. *Manufacturing & Service Operations Management, 4*(2), 133–170.

Shah, N. (2005). Process industry supply chains: Advances and challenges. *Computers and Chemical Engineering, 29*, 1225–1235.

Sodhi, M. S., Son, B. G., & Tang, C. (2012). Researchers' perspectives on supply chain risk management. *Production and Operations Management, 21*(1), 1–13.

Sokolov, B., Dolgui, A., & Ivanov, D. (2018). Optimal control algorithms and their analysis for short-term scheduling in manufacturing systems. *Algorithms, 11*(5), 57.

Sokolov, B., Ivanov, D., & Dolgui, A. (Eds.). (2020). *Scheduling in Industry 4.0 and cloud manufacturing*. Springer, ISBN 978-3-030-43176-1.

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

Spiegler, V. L. M., & Naim, M. (2017). Investigating sustained oscillations in nonlinear production and inventory control models. *European Journal of Operational Research, 261*(2), 572–583.

Spiegler, V. L. M., Potter, A. T., Naim, M. M., & Towill, D. R. (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.

Surana, A., Kumara, S., Greaves, M., & Raghavan, U. N. (2005). Supply-chain networks: A complex adaptive systems perspective. *International Journal of Production Research, 43*(20), 4235–4265.

Tan, B. (2015). Mathematical programming representations of the dynamics of continuous-flow production systems. *IIE Transactions, 47*(2), 173–189.

Tang, C. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics, 103*(2), 451–488.

Tang, C., & Tomlin, B. (2008). The power of flexibility for mitigating supply chain risks. *International Journal of Production Economics, 116*, 12–27.

Tang, C. S., & Veelenturf, L. P. (2019). The strategic role of logistics in the Industry 4.0 era. *Transportation Research Part E: Logistics and Transportation Review, 129*, 1–11.

van Hoek, R. (2020). Research opportunities for a more resilient post-COVID-19 supply chain – closing the gap between research findings and industry practice. *International Journal of Operations & Production Management, 40*(4), 341–355.

Wamba, S. F., Dubey, R., Gunasekaran, A., & Akter, S. (2020). The performance effects of big data analytics and supply chain ambidexterity: The moderating effect of environmental dynamism. *International Journal of Production Economics, 222*, 107498.

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

Xu, X., Lee, S. D., Kim, H. S., & You, S. S. (2020). Management and optimisation of chaotic supply chain system using adaptive sliding mode control algorithm. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2020.1735662

Ye, H., & Liu, R. (2016). A multiphase optimal control method for multi-train control and scheduling on railway lines. *Transportation Research Part B: Methodological, 93*(Part A), 377–393.

Zhong, H., & Nof, S. Y. (2020). *Dynamic lines of collaboration. Disruption handling & control*. Springer.

Zhao, K., Zuo, Z., & Blackhurst, J. V. (2019). Modelling supply chain adaptation for disruptions: An empirically grounded complex adaptive systems approach. *Journal of Operations Management, 65*(2), 190–212.

Chapter 2
Digital Transformation Process Towards Resilient Production Systems and Networks

Dimitris Mourtzis and Nikos Panopoulos

Abstract Coordinating the digital transformation of globally dispersed factories within global manufacturing networks has become critical for competitiveness. From the procurement of raw materials to manufacturing and logistics, and finally to customer fulfillment, digitization is uniting a once siloed supply chain into an integrated end-to-end digital ecosystem. Similarly, for large and complex supply chains, digital transformation has the potential to drive efficiencies, boost innovation, reduce risk, and ensure the flawless operation, increasing the resilience to the disruptions of the production network. In the increasingly competitive global landscape, the Industrial supply chains cannot afford to lose operational efficiencies or ethical practices. Their mission must be to provide high-quality products to customers in a timely, responsible, efficient, and cost-effective manner. Those businesses that pursue their digital goals while also focusing on sustainability will be more resilient and well-positioned for long-term success. Thus, digital transformation achieves the resilient conditions to stay in business during mandatory shutdowns and activity restrictions. To that end, the aim of this chapter is to present a review on the adoption of Industry 4.0 technologies towards accelerating the digital transformation of global production networks. Additionally, a framework for digital transformation and business model change in Small Medium Enterprises (SMEs) during unproved disruption (i.e., pandemic) is presented.

Keywords Digital transformation · Industry 4.0 · Resilience · Disruption

Acronyms

AI Artificial Intelligence
AR Augmented Reality

D. Mourtzis (✉) · N. Panopoulos
Laboratory for Manufacturing Systems and Automation (LMS), Department of Mechanical Engineering and Aeronautics, University of Patras, Rio Patras, Greece
e-mail: mourtzis@lms.mech.upatras.gr

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_2

BEA	Bureau of Economic Analysis
CAGR	Compound Annual Growth Rate
CNC	Computer Numerical Control
GPN	Global Production Networks
GDP	Gross Domestic Product
ILO	International Labor Organization
ISN	Intertwined Supply Network
JIT	Just in Time
MP	Mass Personalization
MPP	Mass Personalization Paradigm
RQ	Research Questions
SME	Small Medium Enterprise
SC	Supply Chain
SCN	Supply Chain Network
SCR	Supply Chain Resilience
SCRM	Supply Chain Risk Management
SCV	Supply Chain Viability
US	United States
VR	Virtual Reality

2.1 Introduction

The focus of logistics research in the 1940s and 1950s was on how to use mechanization (e.g., pallets and pallet lifts) to improve labor-intensive material handling processes, as well as how to make better use of space through racking and better warehouse design and layout. Pallets were widely used as the "unit load" concept grew in popularity. This concept was extended to transportation management in the mid-1950s with the development of intermodal containers and the ships, trains, and trucks needed to transport them. The evolution of Supply Chain Management (SCM) has been marked by a growing degree of integration of separate tasks, a trend that was highlighted in the 1960s as a key area for future productivity improvements due to the fragmentation of the system. Although the logistics tasks have remained largely the same, in the 1970s and 1980s, they were split into two distinct functions related to materials management and physical distribution. Since the 1980s, supply chain management has become increasingly important in business operations. Even though supply chains have existed for a long time, the term SCM was not coined until 1983. Maybe the most significant trend in logistics in the 1980s was that it was beginning to gain widespread recognition in industry as a very expensive, very important, and extremely complex process. Company executives realized that if they were willing to invest in trained professionals and new technology, logistics could help them significantly improve their bottom line (Ballou, 2007).

The way supply chains are used has changed dramatically over the last few years, and they are now more complex than they have ever been. Next, even though "Supply Chain," has evolved into a collection of cross-functional terms that refer to a wide range of business processes all over the world. In the 1990s, as globalization prompted functional integration and the emergence of logistics in its true sense, all elements of the supply chain were brought under a single management perspective. The advent of Enterprise Resource Planning (ERP) systems in the 1990s fueled the logistics boom even more. These systems were inspired in part by the success of Material Requirements Planning systems developed in the 1970s and 1980s, in part by a desire to integrate the numerous databases that existed in almost every company but rarely communicated with one another, and in part by fears that existing systems would fail catastrophically due to their inability to handle the year 2000 date. With the advent of supply chain management, however, only modern information and communication technologies allowed for a more complete integration. It enables the integrated management and control of information, finance, and goods flows, as well as the development of new manufacturing and distribution systems. SCM has evolved into a complex series of activities aimed at maximizing value and increasing competitiveness. However, supply chains are becoming far more complex than companies had anticipated. Businesses began utilizing multiple functions within their supply chains in the 2000s to better utilize their resources and become more efficient than ever before. In spite of some significant problems in getting the Enterprise Resource Planning (ERP) systems installed and working, by 2000, most large companies had installed ERP systems. The result of this change to ERP systems was a tremendous improvement in data availability and accuracy. The new ERP software also dramatically increased recognition of the need for better planning and integration among logistics components. The result was a new generation of "Advanced Planning and Scheduling (APS)" software (MacCarthy et al., 2016).

Consumers all over the world are becoming increasingly involved in our supply chains, and businesses are adapting by adding a variety of functions to their supply chains in order to be more efficient than their competitors. Companies now have a lot of data networking access, which can help them succeed if used correctly. More recently, the evolution of both physical distribution and materials management has been dominated by the increasing level of automation of supply chains (Prince, 2000). This digitalization is especially noticeable in distribution centers, which have seen a significant push towards automation in areas like storage, materials handling, and packaging. Automated delivery vehicles may become a reality as a result of automation (Lee & Billington, 1995) (X). Finally, as per Ivanov et al. (2022) Cloud supply chain is a business model for designing and managing a supply chain network based on cloud-enabled networking of some third-party physical and digital assets. The "Supply chain-as-a-service" paradigm integrates Industry 4.0 concepts and technology with digital platforms emerging in the "cloud supply chain." The key characteristics of the cloud supply chains are:

- Multi-structural dynamics
- Platforms, digital supply chains, ecosystems, and visibility
- Dynamic service composition with dynamically changing buyer/supplier roles
- Resilience and viability; and
- Intertwined supply networks and circular economy

To summarize, the Supply Chains (SCs) are the backbone of global commerce. As such ensuring an uninterrupted flow of goods throughout the supply chain is critical for the economy (Tang, 2006). Annually, it is estimated that USD2 trillion is lost due to SC disruptions that could have been avoided (Gross et al., 2018). Additionally, Coronavirus-related SC disruptions have been reported by 94% of Fortune 1000 companies (Sherman, 2020). Therefore, this issue with the unexpected COVID-19 pandemic has received much more attention. The importance and the evolution of the Supply Chain Management towards the Cloud Supply Chain are highlighted in Fig. 2.1.

E-commerce is divided into two dimensions. Business-to-Business (B2B) or Business-to-Consumer (B2C) are the first two dimensions that define the parties. The transactional nature is defined by the second dimension. There are several types of services available. Sell-side servers are online storefronts and catalogs that handle the entire purchase process, from item selection to payment. The ability to enter and fulfill purchase orders is provided by buy-side servers. Both buyers and sellers can use marketplace applications to create electronic communities (Mourtzis et al., 2021b). Before, during, and after the transaction, e-commerce innovations aim to reduce the cost of procurement. E-commerce eliminates the need to convert computer files into paper documents at every stage, a process that is prone to errors, delays, and the use of expensive clerical staff. E-commerce streamlines the process by facilitating transactions through Web sites and E-mail (EDI) (see Fig. 2.2).

2.1.1 Supply Chain Management Initiatives

Organizations and their trading partners can use supply chain management initiatives to implement industry best practices and reap the benefits of SCM. A variety of supply chain management initiatives exist in various industries with the goal of guiding organizations towards the ultimate SCM vision, which includes the integration of all intra-firm and interfirm policies and processes. New SCM initiatives propose closer, more collaborative trading partner relationships as new information technology and process optimization strategies become available and more developed within industries. Himmilman (1996) proposed a set of strategies that build on each other along a continuum of commitment and complexity in his study of relational change strategies. Based on that study, Ham et al. (2003) elaborated the model to create a framework for organizing different types of SCM initiatives based on the level of complexity and commitment. They argue that as we approach a level of strategic integration among organizations, the complexity of various types of SCM initiatives increases, necessitating cumulative levels of organizational commitment. Having established that SCM initiatives are becoming increasingly complex, it is concluded that this inherent complexity necessitates a corresponding increase in organizational commitment. Four major levels of management in organizations for the purposes of our framework are distinguished: infrastructure, operations, tactical, and strategic management. As the level of

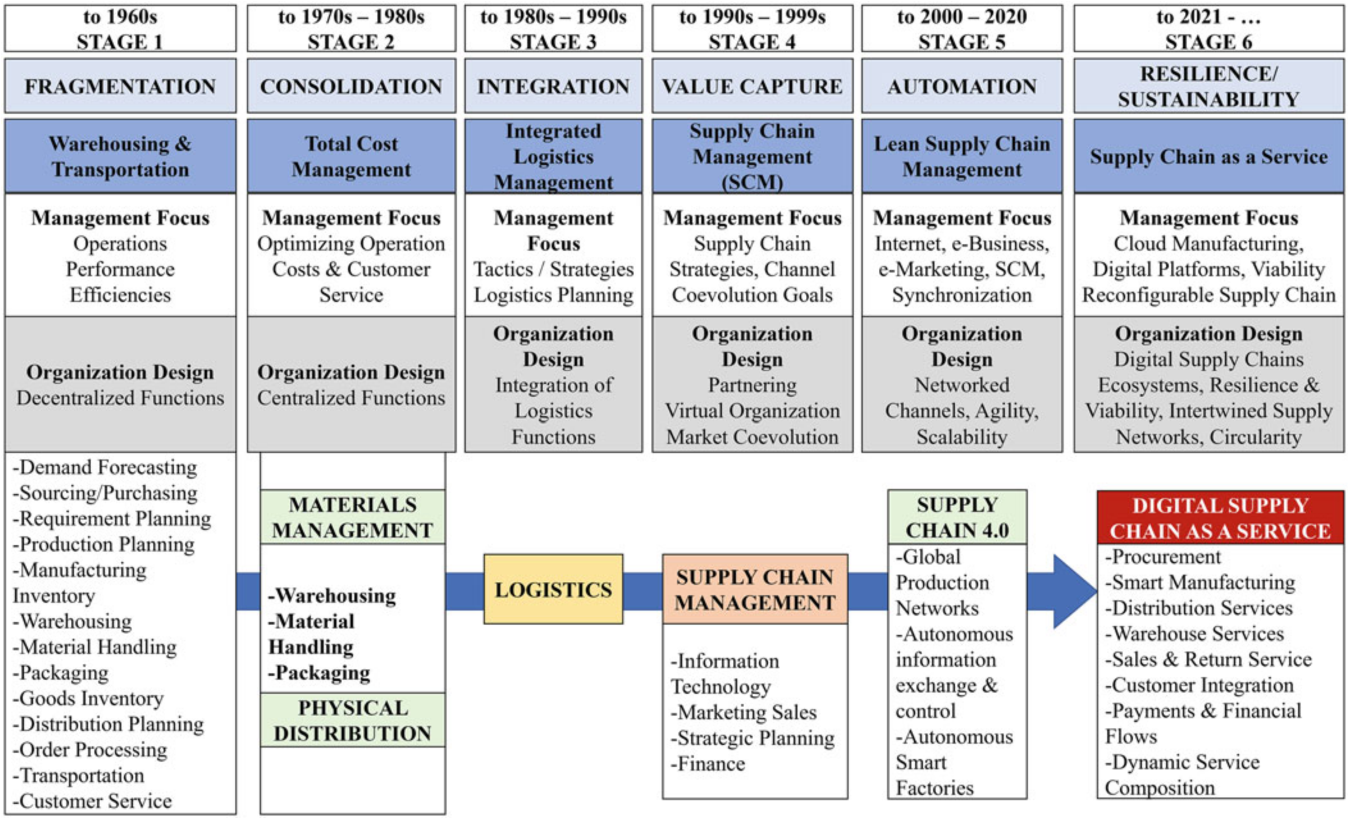


Fig. 2.1 Evolution of Supply Chain Management (Adapted from Daud & Zailani, 2011; Ivanov, 2020b; Dolgui et al., 2022). The current situation of e-commerce

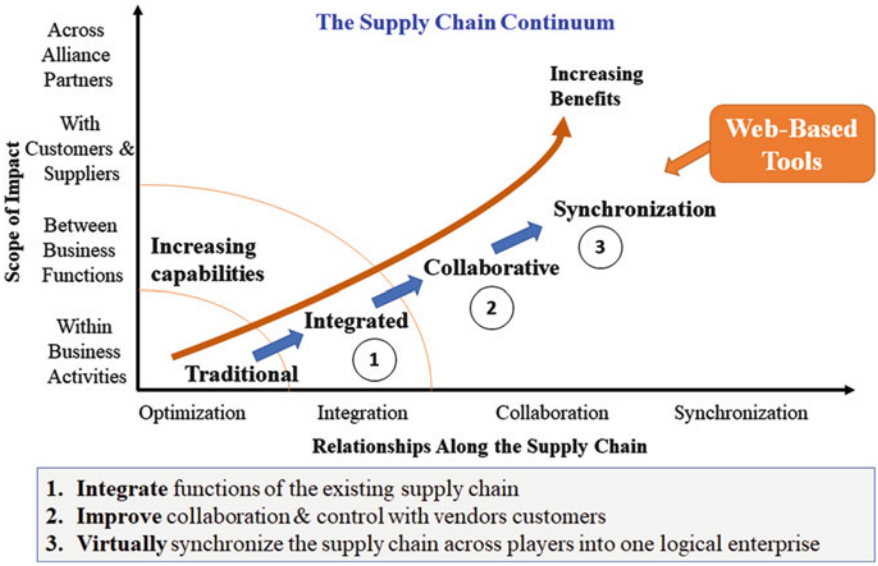


Fig. 2.2 The Supply Chain Continuum—Web-based entrants are making synchronization and the associated benefits achievable (Adapted from Lee & Anderson, 2000)

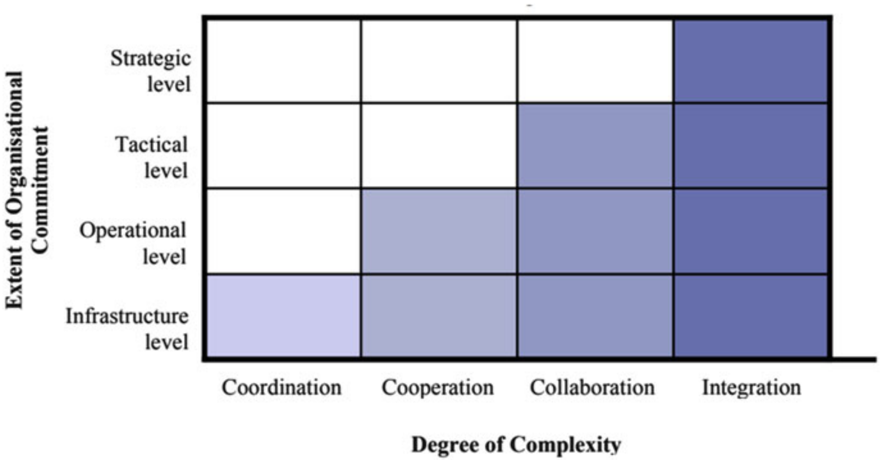


Fig. 2.3 The Complexity-Commitment Continuum (Adopted from Ham et al., 2003)

commitment required by organizations in terms of time, resources, and managerial attention to achieve the visions increases as we approach integration-type initiatives, the level of commitment required by organizations in terms of time, resources, and managerial attention to achieve the visions increases as well (Fig. 2.3).

2.1.2 Building Supply Chain Resilience Through Digital Transformation

A disruption on either the supplier or customer side of today's tightly coupled supply chains can easily wreak havoc across the entire supply chain network (SCN). The pandemic caused significant supply chain disruption, requiring leaders to right-size their operations and embrace digital capabilities that protect supply chains from future disruptions as we move into the post-COVID-19 reality. Companies across all industries are doubling down on advanced technology investments, which have proven to be the lifeblood of the organization, from blockchain to artificial intelligence (AI), machine learning, and intelligent automation. During the COVID-19 pandemic, global supply chains are confronted with both a supply shortage and a shrinking demand, which could result in disruptions propagating forward and backward simultaneously or sequentially (Ivanov & Dolgui, 2020; Quieroz et al., 2020; Ivanov & Das, 2020; Paul & Chowdhury, 2020). In Fig. 2.4, the Closed-Loop Control Systems of the Control Theory has been parallelized to a Closed-Loop Crisis Response Framework that explains the Supply Chains Disruption.

Because of the propagating effects, the effects of a local disruption are unpredictable, making it difficult to plan for and manage. Traditional supply chain risk management (SCRM) typically begins with risk identification and ends with various strategies for managing the risks that have been identified. Because of the propagating effects, the effects of a local disruption are unpredictable, making it difficult to plan for and manage. Traditional SCRM typically begins with risk identification and ends with various strategies for managing the risks that have been identified (Sawik, 2020; Yoon et al., 2018; Baghersad & Zobel, 2021).

Technological unemployment is observed in every industrial revolution, but it is merely a disposition of human workforce, since it is reported that there will be a

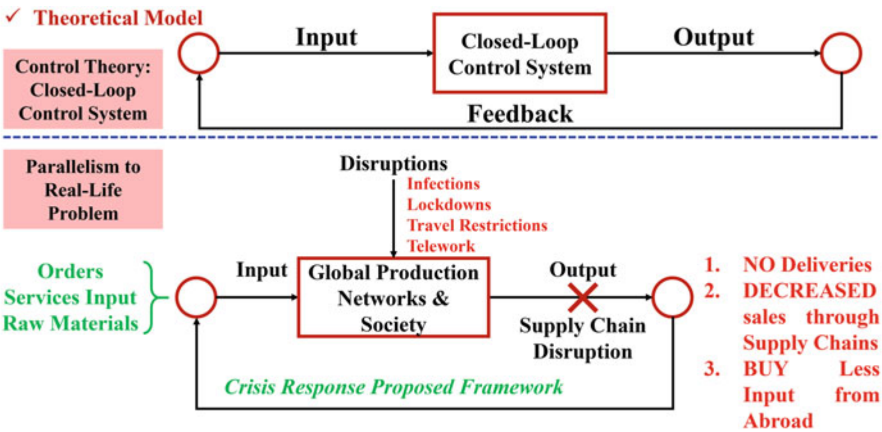


Fig. 2.4 Closed-Loop Crisis/Disruption Response Framework

positive change in the overall job count globally (Peters, 2019). The SARS-CoV-2 pandemic has had a far greater negative impact on global economic growth than anything experienced in nearly a century. According to estimates, the virus slowed global economic growth to a −4.5% to −6.0% annualized rate in 2020, with a partial recovery of 2.5% to 5.2% expected in 2021. In 2020, global trade is expected to fall by 5.3%, but it is expected to grow by 8.0% in 2021 (CRS Report, 2021). The Bureau of Economic Analysis (BEA) reported that United States Gross Domestic Product (GDP) fell 9.0% in the second quarter of 2020 compared to the previous quarter, or at an annualized rate of −31%, the largest quarterly decline in US GDP in the past 70 years (GDP, 2020).

The International Labor Organization (ILO) estimated that 93% of the workers worldwide were living under some form of workplace restrictions because of the global pandemic (ILO, 2021), and that 8.8% of global working hours were lost in 2020 compared to the fourth quarter of 2019, an amount equivalent to 255 million full-time workers.

The COVID-19 pandemic has changed the global perspective regarding the technological unemployment. By extension, the global priority became to ensure that the virus will not spread, and people remain safe and healthy. Other analysts predicted that the pandemic would have three major effects on the workplace (McKinsey Global Institute, 2021):

- Establishing telework as a permanent presence, with 20–25% of workers in developed economies and 20% in developing economies working from home three–five times per week, potentially reducing demand for public transportation, restaurants, and retail stores.
- Expanding e-commerce, which may disrupt travel and leisure jobs, low-wage jobs in brick-and-mortar stores and restaurants and increase jobs in distribution centers.
- Accelerating the adoption of artificial intelligence (AI) and robotics.

The above-mentioned challenges, created a situation in which people who were working, suddenly had to stay home and if remote working was not applicable, then they should rely on their government to provide them an income. It is very interesting to observe the business model changes that this pandemic created and how it worked as a catalyst for digital transformation. The Industry 4.0 technologies have a vital role in this whole process, since remote working relies on computing power and data management, healthcare system in many occasions rely on robots to treat patients, and people shop online for the products they need, while the supply chain has to manage the overload of business-to-consumer sales (Acioli et al., 2021). It becomes evident from the changes that societies are facing right now, a new model can be envisioned from the countermeasures taken against COVID-19. Remote working could be the solution to work-life balance, but social control and movement facilitation constitute a challenge for privacy (Pew Research Center, 2021). Therefore, the aim of this chapter is to examine how a disruption such as the COVID-19 pandemic impacted the business landscape and to propose a Conceptual Crisis Response Framework, as an outcome of best practices observed in the literature.

The rest of the paper is structured as follows. In Sect. 2.2, the research methodology is presented, and the relevant literature is investigated. In Sect. 2.3, the review focuses on the COVID-19 as a catalyst for business models and in Sect. 2.4 the proposed conceptual framework for digital manufacturing transformation is discussed. Finally, Sect. 2.5 presents interesting statistics about the impact of the pandemic and in Sect. 2.6 the paper concludes as well as future development directions are discussed.

2.2 Literature Review

2.2.1 Supply Chain Management

The concept of SCM was introduced in the 1980s. SCM has undergone numerous and significant changes from its original state since then. Despite the popularity of SCM in the academic and business worlds. Wee et al. (2015) argue that there is still much confusion as to why some writers define SCM in operational terms, such as the flow of raw materials and products, while others define it as a management philosophy, a management process, or an integrated system. The main purpose of SCM is to manage the flow of information, products, and services across a network of customers, enterprises, and supply chain partners (Russell & Taylor, 2009). Many authors considered the SCM and the logistics as synonym terms. Even though SCM includes logistic management activities, there is a significant distinction between SCM and logistics. The movement of materials within an organization's premises is the responsibility of logistics. SCM, on the other hand, includes the management and planning of all procurement, sourcing, and conversion activities, as well as all logistics management activities. The most important feature of the SCM is that it includes the coordination and collaboration of all the partners (e.g., suppliers, customers, intermediaries, or service providers) (Mourtzis et al. 2021a).

2.2.2 Supply Chain Disruption Propagation/Ripple Effect

Supply chains are complex, dynamic network systems that change size, shape, and configuration over time (MacCarthy et al., 2016). Supply chain structural dynamics theory investigates changes in network topology and design, as well as methods for managing and optimizing supply chain processes when these changes occur (Ivanov & Dolgui, 2021b). New disruptive technologies (e.g., blockchain) and disruption risks (e.g., natural disasters and the ripple effect) can be considered in the context of supply chain structural dynamics (Dolgui et al., 2018).

Due to the significant global economic loss caused by various disruption events such as the 2020 COVID-19 Pandemic, supply chain disruption propagation, also known as the ripple effect, has investigated extensively by academia recently (Ivanov 2020a, 2020b). The term "disruption propagation" or "ripple effect" describes how an operational failure at one SCN entity causes operational failures at other SCN entities (Dolgui et al., 2018). There are studies on disruption propagation with a variety of approaches. To begin with, modeling and simulation methods are widely used in this field (Wenz et al., 2014), including agent-based simulation from a complex network perspective, risk propagation using Bayesian network approaches (Hosseini et al. 2020), numerical models to simulate indirect effects in the global supply chain using the input-output model (Zeng & Xiao, 2014), and the entropy approach (Mourtzis et al., 2019) to study the vulnerability of cluster SCN during cascading failures (Kinra et al., 2020).

The ripple effect, according to Dolgui et al. (2020), refers to structural dynamics and describes a downstream propagation of demand fulfillment downscaling in the supply chain as a result of a severe disruption. Additionally, the "Ripple effect describes the impact of a disruption on supply chain performance and disruption-based scope of changes in supply chain structures and parameters," according to Ivanov et al. (2014).

2.2.3 Resilient Manufacturing

While SC disruption management (i.e., unexpected events with severe negative consequences such as tsunamis, fires, or strikes) has become a mature research topic over the last two decades (Sawik, 2020), the pandemic is considered as a new type of disruption unlike any seen before (Ivanov & Das, 2020). The outbreak of the pandemic and the resulting global pandemic has highlighted the critical role of SCs in providing goods and services to society in a secure manner. The pandemic tested SCs in terms of their resilience (i.e., ability to withstand), flexibility (i.e., ability to adapt), and recovery (i.e., ability to restore operations and performance after a disruption), highlighting the critical role of resilience in managing SCs in this volatile world (Wood et al., 2019).

Throughout this disruption, several resilience-related research questions (RQ) have arisen, such as whether local SCs are more resilient than global SCs (Ivanov & Dolgui, 2021b):

- RQ1: Is it true that SCs that follow lean principles (such as Just-in-Time and single sourcing) are less resilient than companies that have a high cycle and safety inventory?
- RQ2: Can traditional resilience assets (such as risk inventory, capacity buffers, and backup suppliers) help in pandemic situations?
- RQ3: Are SCs that use advanced digital twins, as well as visibility and analytics, more resilient?

- RQ4: Will post-pandemic resilience take precedence over efficiency (i.e., should we expect a paradigm shift from "design-for-efficiency" to "design-for-resilience?"

The Digital Transformation that AI enabled for manufacturing plants and supply networks poses a great opportunity for increasing the resilience and efficiency of manufacturing firms. Additionally, an intertwined supply network (ISN) is a collection of interconnected supply chains (SC) that ensure the supply of goods and services to society and markets. The ISNs provide services to society (e.g., food service, mobility service, or communication service) that are required for long-term survival. The authors, Ivanov and Dolgui (2020), present a conceptual novel decision-making environment of ISN viability. Moreover, with digital transformation, vast amounts of data can be transferred for improving data-driven decision-making process and increase reactivity of firms to the volatile market demands, since information flows faster within the business. Such factories are called "Smart Factories" and are based on smart technologies, such as process automation, robotics, Internet of Industrial Things, Big Data, Digital Twin, Artificial Intelligence (AI), and so on (Mourtzis, 2020). A great example of resilience and flexible manufacturing is the Ford and General Motors production line that started producing ventilators for COVID-19 patients (WEF, 2020). These companies had idle factories and decreased demand in their products, so they started producing personal protective equipment and ventilators in order to assist the United States government in fighting this healthcare crisis. Other innovative approaches that can be applied in Manufacturing are automated material and transportation systems, predictive maintenance tools, AI-based forecasting tools, Virtual and Augmented Reality (VR and AR, respectively) and wearable devices, and discrete event simulation models (Wuest et al., 2020; Mourtzis et al. 2021b). The abovementioned solutions can optimize the response time in external changes and create solutions for many problems that can occur. The automated transportation system within a plant can guarantee a 24/7 internal supply of materials and products and at the same time ensure that the human element is protected from accidents within the workplace.

The challenges that this global crisis has created for the manufacturing industries around the globe are primarily the demand shocks and the regulations regarding human interaction. Automotive industry is being forced to shut down factories to ensure the safety of workers, they experience the travel bans and the overload of supply chain. Supply Chain (SC) shocks and adaptations during the COVID-19 pandemic, as well as post-pandemic recoveries, provide incontrovertible evidence for the urgent need for digital twins for mapping supply networks and ensuring visibility (Ivanov & Dolgui, 2021a).

2.2.4 Smart Manufacturing

Smart Manufacturing is defined as "a broad category of manufacturing that employs computer-integrated manufacturing, high levels of adaptability and rapid design changes, digital information technology, and more flexible technical workforce training" (Kusiak, 2018). Smart Manufacturing can also be defined as "the fully integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the smart factory, in the supply network, and in customer needs" (O'Donovan et al., 2016). This concept includes the ability to quickly alter the production levels based on demand, optimize the supply chain operations, efficiently produce, and recycle materials and other used resources. The idea of smart factory is based on interoperable systems, multi-scale dynamic modeling and simulation, intelligent automation, strong cyber security, and interlinked sensors to ensure real-time and reliable information flow (Mourtzis, 2020). Some of the key technologies in the Smart Manufacturing movement include big data processing capabilities, industrial connectivity devices and services, and advanced robotics. The review paper in Budd et al. (2020) identified the ways in which Smart Manufacturing ecosystems can potentially accelerate smart factory initiatives and a summary of digital technologies deployed in public-health interventions for the COVID-19 outbreak, showing key publications, examples, and resources. Many approaches employ a mix of digital technologies and rely on telecommunications infrastructure and internet access. For instance, machine learning is depicted as a separate branch, despite the fact that it underpins many of the other technologies. The data generated by these technologies is frequently fed into data dashboards (Fig. 2.5).

2.2.5 Supply Chain Resilience

An unprovoked disruption like the COVID-19 shows that pandemics and epidemics can seriously disrupt supply chains (SC) around the globe. To that, a systematic analysis of the impacts of epidemic outbreaks on SCs guided by a structured literature review and a framework for operations and supply chain management during the COVID-19 pandemic including six perspectives, i.e., adaptation, digitalization, preparedness, recovery, ripple effect, and sustainability is presented in Queiroz et al. (2020). When supply chains (SC) are exposed to and affected by changes in environmental and operational factors, resilience capabilities enable recovery and adaptation. Digitalization both improves and challenges supply chain resilience (SCR). The development of new paradigms, principles, and models in Supply Chain Management (SCM) in general, and SCR, is influenced by digital technology innovations. Industry 4.0, the Internet of Things (IoT), Big Data analytics, Artificial Intelligence, Advanced tracking and tracing technologies, Wearables, and Additive Manufacturing are all examples of digital technology. As stated in (Supply Chain &

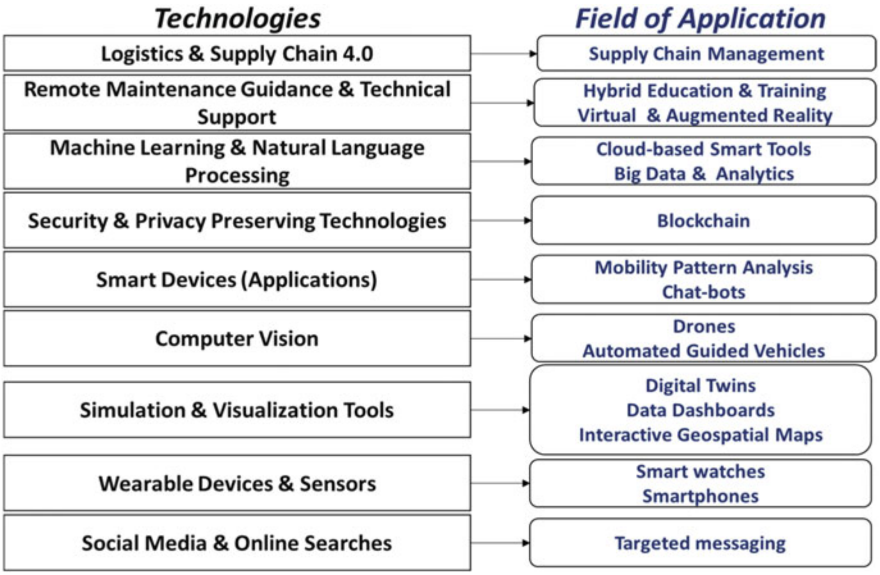


Fig. 2.5 The interconnected digital technologies used in response to COVID-19 (Adapted from Budd et al., 2020)

Operations, n.d.), most Fortune 1000 companies, i.e., 94%, are facing disruptions in their supply chain due to COVID-19. The scale of this disruption is a great challenge for supply chain leaders, while the data flow is very fast, and the decision-making process must be performed almost in real-time, to manage the changes imposed by this crisis. The balance between protecting public health and maintaining the global supply chains is crucial and in order to manage the situation and all the healthcare measures. Consequently, guidelines should be followed in every procedure.

The abovementioned challenges could be described as the travel restrictions, combined with the rigid processes that were used before the pandemic to transport products and the high cost of delivering products from the factory to the final consumer. Potential problems in the supply chain are now obvious and it is very hard for many organizations to adjust their operations, and this is even harder if they do not have sufficient technological infrastructure or if they have obsolete operating systems. The customers today have many expectations, ranging from fast delivery to environmental protection, that companies must abide by to retain customers and fulfill their social responsibility. Finally, the supply chain operations are dependent in the human element and as a result, talent shortage in this specific field in combination with the social distancing restrictions creates a situation of high volatility (Randhawa et al., 2020). One positive aspect of the COVID-19 era is that the human workforce is being put back at the center of all activities. Thus, ensuring the well-being and productivity of people is crucial for the survival of an organization. In order to address the abovementioned challenges, businesses, and governments should understand how to properly collect and interpret data, in order to drive the decision-making process, as well as manage the demand curve, inventory size, total production capacity and logistics functions through the whole ecosystem and its stakeholders. The market shock that is now observed in the whole world makes it harder to decide which areas to prioritize in the supply chain, so the demand must be segmented, and health institutions should be number one priority to deliver products. At the same time, the whole customer base should be taken care of and provided with the essential products, meaning that companies must recruit and train people, dedicated in problem solving and managing the vast volumes of products that people order daily. Finally, supply chain viability (SCV) is a new concept in operations management that is gaining traction. As such, Ruel et al. (2021) aim to conceptualize, develop, and validate an SCV measurement scale.

2.2.6 Novel Technologies Utilized for Disruption Response

The real challenge of this pandemic was to design, manufacture, and supply countries around the world with huge volumes of the proper diagnostic tools, medical supplies and personal protection equipment in an extremely short period of time, as well as monitor urban movement and transportations globally with limited resources and most importantly secure public health. The production across all industries and around the globe was affected, while the demand and supply were facing phenomenal variations. When lockdowns were implemented in many countries, only essential stores could remain functional, while other retail shops and corporate offices were forced to either shut down or have their human resources work remotely instead of being in the physical offices. The fight against the pandemic utilized a wide range of novel technologies, for example, Machine Learning was used to study huge databases with viral genomes to lay the foundation for our understanding of the COVID-19. Through these methods, scientists were able to determine the origin and the genetic sequence of the virus (Meraihi et al., 2022). Machine Learning is a subset of AI and is defined as "a computer-based learning achieved by following an algorithm, which operates under a set of instructions or rules, to maximize the chance of a prediction being correct." The problems that arise from such methods are the patient data privacy and the amount of data needed to have an accurate model. Even though these concerns are valid, the amount of time saved, and the efficiency of such methods is undeniable. Without the necessary computer power and the utilization of novel technologies, people would need many months, or even years, to collect, share, examine, and find the patterns that Big Data, Internet of Things, and Cloud Technologies can monitor in real-time, and Artificial Intelligence can process with much greater speed and accuracy, in comparison with a team of human workers (Robinson, 2020). Through sensors, mobile phones, security cameras or other sources, data collection is done automatically, and the Internet of Things systems can transfer the data without human involvement to the officials who need real-time information about the progress of the pandemic. Such examples can be found in Boston, where robots are deployed to conduct patient interviews and through sensors, integrated into the robots, measure the respiratory rate and body temperature. Afterwards, data are transferred wirelessly and collected to the Health Care databases for processing. Ultimately, under this framework of operation, the contact of healthcare workers with infected individuals is minimized (Trieut, 2020).

2.3 Production Networks Modeling and Control Towards Mass Personalization

2.3.1 State of the Research: Case Studies

Epidemic outbreaks are a specific example of SC disruptions. Epidemic outbreaks are a unique type of SC risk that is defined by three distinct characteristics. These elements based on Ivanov (2020a, 2020b) are as follows:

1. The existence of long-term disruptions and their unpredictable scaling.
2. Simultaneous disruption propagation in the SC (i.e., the ripple effect) and epidemic outbreak propagation in the population (i.e., pandemic propagation).
3. Simultaneous disruptions in supply, demand, and logistics infrastructure.

More specifically, Ivanov (2020a, 2020b) defined the characteristics that distinguish epidemic outbreaks as a distinct SC risk. Second, he used the coronavirus COVID-19 and simulation and optimization software to show how simulation-based methodology can be used to examine and predict the effects of epidemic outbreaks on SC performance. Modern manufacturing has to be flexible in order to respond to the demand for highly customizable products. The automotive supply chain is a typical example. The competitiveness level of a company is largely determined by its ability to perform well in cost, quality, delivery, dependability, and speed, as well as innovation and adaptability to the variations of the demand profile (Chryssolouris, 2006).

To that end, Mourtzis et al. (2008) described the design and implementation of a system capable of modeling the supply chain and dynamically querying supply chain partners to provide real-time or near-real-time information on part availability for the production of a highly customizable product. Additionally, they described the details of a software system for determining the time and cost of acquiring the components needed to build the customized product. The method uses Internet-based communication as well as near real-time data collected by Radio Frequency Identification (RFID) sensors. Finally, the feasibility of implementing this approach is demonstrated in a typical automotive case study.

Next, the trend towards customized and the ongoing shift towards personalized products has significant impact on manufacturing companies, as the ever-increasing number of product variants and the expanded pool of cooperating partners vastly expand the number of possible supply chain configurations. This is translated to massive search spaces in terms of decision theory. Metaheuristic optimization methods, which provide a trade-off between the quality of solutions and the computation time, are used to solve these NP-hard problems. The Simulated Annealing and Tabu Search methods were used to model and solve two supply chain configuration problems by Mourtzis and Doukas (2015). More specifically, the results of a custom Intelligent Search Algorithm and an Exhaustive enumerative method are compared to the performance of the identified solutions in terms of optimization of multiple conflicting criteria. Additionally, a web-based application platform utilizing the algorithms has been developed. Real-world case studies from the automotive and CNC laser welding machine building industries are used to validate the approach.

Moving on, the local economy has evolved into a global and highly competitive economy over the last few decades. The value-added chain in the global manufacturing network was reshaped as a result of market globalization and technological innovations. Industries began to operate on a global scale, broadening the scope of their operations. Up until the 1990s, the export of finished goods to foreign markets was the dominant theme in international trade, and it has gotten even more attention in the last decade (Abele et al., 2006). The transition from rigid, centralized production plants to networked production began in the 1990s. The first phase of global expansion was fueled by large corporations' increasing internationalization in order to take advantage of low factor costs. Development of new sales markets and local just-in-time delivery systems were also important drivers (Porter, 2007).

Decentralized manufacturing approaches, which have largely replaced centralized practices, have progressed thanks to the Internet, which has helped to coordinate the efforts of the manufacturing network. Manufacturing approaches that are decentralized have been extensively researched in literature (Mourtzis et al., 2012, 2013). Nowadays, industrial companies are part of global production networks (GPNs). Thus, a comprehensive scientific overview of those networks is presented in the state-of-the-art paper by Lanza et al. (2019). More specifically, a framework for designing and operating GPNs is introduced to close this gap. However, the demand for unique products is increasing all the time, pushing mass customization to its limits and ushering in the mass personalization paradigm (MPP). MPP strives to create products that meet specific customer needs while also being cost and resource efficient. However, global production networks face challenges because of the complexity associated with MPP as a result of increasing variants and unpredictability in demand of GPNs. These issues have been addressed by recent developments in cloud manufacturing (CM) and Industry 4.0 in Lanza et al. (2022). The purpose of the chapter is to demonstrate the implications of MPP for the design and management of GPNs, as well as to identify the enabling concepts required to address those implications.

The mass personalization (MP) paradigm encourages end users to participate more actively in the manufacturing process. Furthermore, manufacturers strive to remain competitive while also establishing trust with their customers and learning about their preferences. The growing demand for personalized products, combined with volatile market demand, influences GPNs of Industries. GPNs are being developed, planned, and operated by manufacturers and service providers to address shorter product life cycles and increased product complexity. Consumers, aided by social media and digital devices, are constantly dictating what, when, and where they want a commodity. As a result, mobile apps and automated decision-making methods are critical for recognizing and fulfilling consumer preferences. Thus, Mourtzis (2022) aims to identify and highlight the implications of manufacturing network design and planning in the MP environment.

Focusing more on supply chains, Dolgui et al. (2022) discuss the methods and technologies that can support digital transformation and the development of innovative supply chain concepts in the MP environment. More specifically, the authors focus on reconfigurable supply chains, also known as an X-network. This is a network that is designed to adjust supply chain capacities and functionality in response to market volatility in a cost-effective, responsive, sustainable, and resilient manner. It is data-driven and adaptable. Improved flexibility, as well as improved supply chain planning and controlling strategies, can be achieved using Industry 4.0 key technologies.

2.3.2 Disruptions as a Catalyst for Business Models Change

Governments and health authorities around the world have asked businesses to repurpose their production lines and supply chains due to short supplies in critical equipment such as protective gear for healthcare professionals, testing kits and ventilators for patients. As a result, global manufacturers in almost every industry, from fashion to food and beverages, have taken the initiative to shift operations to combat the crisis, by changing the business model of their company. The business model shift of some global companies during the pandemic is presented in Table 2.1. Without a doubt, the pandemic is transforming the way we live and work. We are entering a "new normal" that will look significantly different from where we are now as a result of the immediate and long-term adjustments being made in response to the virus's effect on health systems, the economy, and working patterns. Most organizations are now undertaking the Industrial Transformation journey, whether they realize it or not. Industry 4.0 is a broad vision with well-defined frameworks and reference architectures, primarily defined by the integration of physical industrial assets with digital technologies in so-called cyber-physical systems. Next, a three-part approach is outlined by Davenport and Redman (2020) to be used as a crisis response framework. The three aspects cover the following:

(a) *Recover*: keep the lights on during immediate crisis response
(b) *Regroup:* refresh the Digital culture and pivot customer proposition and
(c) *Renew:* seek out new opportunities as we prepare for life in the "new normal"

Table 2.1 Manufacturing industries before and during pandemic (Lewis, 2020)

No	Companies	Domain	Before pandemic	During pandemic
1	Ford	Automotive Industry	Vehicles	Modified respirator and ventilation
2	Tesla-Giga Factory	Automotive Industry	PV Cells	Ventilators
3	Airbus	Automotive Industry	Aircraft products	Ventilators
4	Mercedes-AMG High-Performance Powertrains	Automotive Industry	Formula 1 engines	Continuous positive airway pressure machines
5	Dyson	Tech Company	Vacuum cleaners & hand dryers	Ventilators

2.3.3 Digital Transformation Challenges in the Manufacturing Industry

For the overall success of digital implementation in manufacturing, a well-defined digital transformation strategy is essential. From development and production to advanced quality control, delivery, and analysis, the strategy should cover every aspect of business activity. Understanding the challenges that manufacturing organizations face along the digital transformation journey is critical to effectively embrace digital technology. Several challenges must be addressed and handled as part of the digital transformation roadmap. Table 2.2 shows some of the challenges to consider when implementing digitalization in manufacturing (Albukhitan, 2020).

2.3.4 Digital Transformation Strategy

Digital transformation necessitates a digital transformation strategy that considers the goals, current situation, and how to proceed on a transformational journey in a logical and cohesive manner. Companies all over the world are undergoing digital transformations to improve business processes and develop new capabilities and business models. More specifically, they need to develop a digital transformation strategy and build bridges across multiple domains, including information, data, processes, technologies, human aspects, and more. Answering key questions like "what," "why," "how," and "who" is the first step in developing a digital transformation strategy (Fig. 2.6). A digital transformation strategy connects the current state with the long-term vision. A digital transformation strategy looks at building blocks and the links among them, as well as barriers and new bridges to overcome. This happens because digital transformation is holistic by definition and necessitates integration and collaboration (Matt et al., 2015).

Table 2.2 Top challenges faced by manufacturing for digital transformation

No	Challenges	Description
1	Traditional processes	It is difficult to rely on traditional paper-based processes and operate in silos now that everything is connected digitally; manual, time-consuming processes have no place in today's world
2	Resilience	Many technicians are resistant to change in their workplace because it disrupts their comfort zone, and many manufacturing employees see digital disruption as a threat
3	Legacy business mode	Manufacturers have grown accustomed to their old systems
4	Limited automation	Many repetitive, redundant, and time-consuming tasks are completed manually by a task force, resulting in many man-hours and a high cost.
5	Budget restrictions	Leading a manufacturing facility through the digital transformation journey necessitates a significant investment.
6	Absence of relevant knowledge	Integrating digital technologies into manufacturing necessitates increasing employee knowledge.
7	Inflexible structure	To function properly, the organization requires new technologies and business models. It has the potential to yield a lot of positive outcomes as the organizational structure allowing for better employee status and other improvements
8	Security	The operation network and systems will be exposed to the internet, cybersecurity is a major concern for any digital transformation project

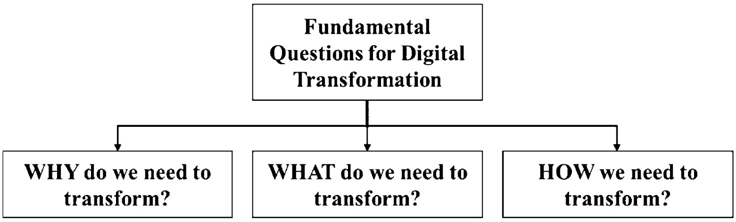


Fig. 2.6 Digital transformation strategy fundamental questions

2.3.5 A Holistic Approach of Digital Business Transformation

The term "Digital Transformation" or "Digital Business Transformation" is used as an umbrella term for changes in meanings that are not strictly related to business, such as evolutions and changes in government and society, regulations, and economic conditions. Processes, interactions, transactions, technological evolutions, changes, internal and external factors, industries, stakeholders, and so on are all covered by digital transformation. Although organizations around the world face similar challenges, goals, and characteristics, there are significant differences between industries, regions, and organizations. Technological evolutions and technologies, ranging from cloud computing, big data, advanced analytics, artificial intelligence, machine learning, and mobile/mobility to the Internet of Things and more recent emerging technological realities, are (Heavin & Power, 2018; Pihir et al., 2018):

1. Enablers of digital transformation
2. Causes of digital transformation needs (among others, as they impact consumer behavior or reshape entire industries, as in the digital transformation of manufacturing), and/or
3. Enablers of digital transformation need

2.4 Framework for Digital Transformation in Manufacturing

2.4.1 Digital Acceptance

Consumers expect a personalized experience, such as product recommendations and communications, and are willing, if not eager, for that experience to take place online. Life science companies are also moving away from traditional door-to-door sales reps and towards digital salesforce automation. According to a UBS survey, nearly 40% of Chinese respondents increased their online shopping in early April, compared to the worst days of the crisis, and three-quarters said they planned to continue the practice in the future (Financial Times, 2022). This brings together marketing, operations, and sales teams on a single platform, as well as 24/7 training, sales forecasting, physician communications, and analyzed customer data across the customer lifecycle. This integration provides real-time visibility to help make better decisions and save money. The widespread adoption of stay-at-home orders accelerated the digital trend, as millions of people found themselves working remotely, collaborating, and supporting their work using digital systems, and millions more were homeschooled using online learning technologies. Therefore, many of these changes in patterns are expected to continue. Many companies are rethinking their supply chain models and how they can make better leverage technologies to support digital activities as a result of the vast virtual shopping, working, educating, and entertaining opportunities.

2.4.2 SCM Towards Reduced Complexity and Uncertainty

The scope of efficient supply chain management is to reduce complexity and uncertainty. New technologies enable the coexistence of digital enablers and humans across various supply chain processes and activities, which can aid in the achievement of these two goals (Fig. 2.7) (KPMG, 2020):

Therefore, a variety of approaches and technological solutions can be used to provide precise supply chain visibility. This allows for real-time decision-making and responsiveness, which will be crucial in the future for companies to monitor and adapt to changes in customer behavior and supply chain variability.

Furthermore, a number of disruptive technologies enable the digitalization of the manufacturing sector during the Industry 4.0 revolution. The IoT, in conjunction

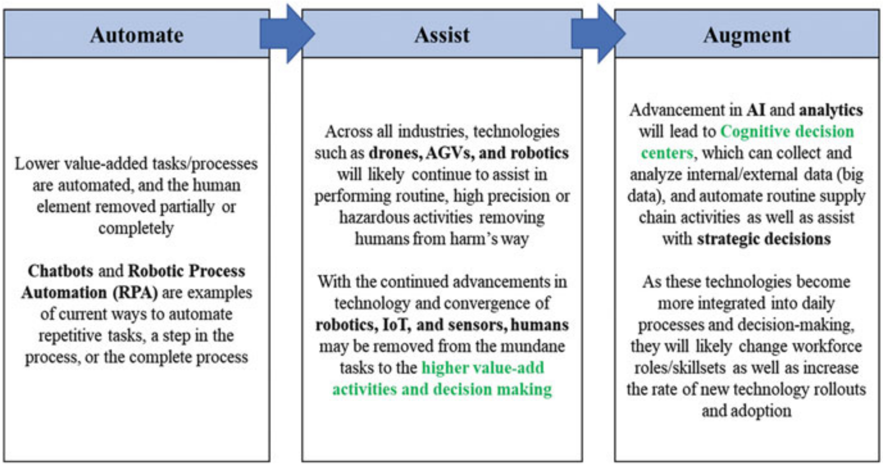


Fig. 2.7 Future proof of the supply chains with Industry 4.0 technologies

with Big Data analytics, Virtual and Augmented Reality, and cloud technologies, aims to integrate and analyze data from multiple sources and companies, share outcomes across the value chain, ensure integration with physical production assets, and rethink the design of traditional manufacturing systems. Every manufacturing phase, from design to final products, is affected by the Industry 4.0 paradigm. Manufacturing companies can easily and effectively gather the pulse of the market and customers' needs thanks to the increased use of internet-connected mobile devices and social media, allowing them to offer high-value-added products and solutions to their customers. Companies can use smart sensing devices, mobile devices, and advanced Human-Machine Interfaces (HMIs) to sense the current state of their production and retrieve valuable feedback. This vast amount of data generated by various sources can be combined and analyzed to provide useful information and insights to planning systems, allowing them to become adaptive, autonomous, and self-learning. The adoption of industrial communication protocols (e.g., OPC Unified Architecture (UA), ROS (Robot Operating System), etc.) is primarily used to integrate data from various sources. These protocols allow for data integration and efficient data transfer between various systems. One of the most significant challenges posed by the large amount of data is its analysis. Advanced algorithms for prediction and integrated planning can make better use of the data that has been analyzed, increasing the efficiency and productivity of systems. Cloud technology is also used in the context of the Industry 4.0 paradigm to improve interoperability and communication among various systems, store generated data, and support ubiquitous data access. Cloud manufacturing enables the creation of various services and their application in accordance with the needs and business models of each industry. Thus, Industry 4.0 technologies seek to unlock new value potential by introducing new business models. The low cost of IoT devices and apps allows businesses, particularly SMEs (Small Medium Enterprises), to go digital and strengthen their position in the global value chain. Therefore, the actual transmission from traditional manufacturing to the Industry 4.0 paradigm is presented in Fig. 2.8.

From simple Entrepreneurial Resource Planning (ERP) software up to end-to-end business solutions, or even having a functional website, a lot of corporations neglected following the trends shaped by new technologies and refused to radically challenge the status quo in the industry. For this reason, when the pandemic reached the doorstep of every single business unit and every country in the world, digital transformation efforts suddenly increased, with many companies turning to e-commerce, and all physical stores for retail trade had to stop operating, as instructed by many governments around the globe. The COVID-19 pandemic was considered as an opportunity by many, to evolve and expand their operations by utilizing innovation and technology (Corver & Elkhuizenm, 2014). Those who did not adapt eventually will seize to exist because of the strict measures applied in the global market, to manage this healthcare crisis. The key areas for digital transformation are technology, data, process, and organizational change capability. These four key areas cannot be analyzed as isolated entities, but they must be developed together. The key to all digital transformation activities is the human capital, and as a result all efforts must start with a clear vision and a roadmap to lead the way. COVID-19's unprecedented supply chain disruption has had serious operational and financial consequences, with planners having to deal with issues such as: (1) demand drops and surges by segment, (2) scarcity of supplies, (3) inventory placement issues, as well as (4) decreased productivity. During the pandemic, Original Equipment Manufacturers (OEMs) and planners were unable to rely on the steady-state models that are at the heart of most existing planning systems. Instead, they have played a critical role for the flow of supply chain data, making decisions based on real-time data. Moreover, according to Solis and Szymanski (2016), the six stages of digital transformation can be categorized as follows:

(a) Stage 1: Business as usual
(b) Stage 2: Present and active
(c) Stage 3: Formalized
(d) Stage 4: Strategic
(e) Stage 5: Converged, and
(f) Stage 6: Innovative and adaptive

Organizations can become more agile, more responsive to changes in demand, and better able to increase and sustain profitability by automating, standardizing, and globally sourcing processes. Competitiveness is becoming increasingly dependent on human intervention and anticipating fast-changing market developments. Agile practices have been successfully adopted by IT organizations, allowing for faster product development and organizational transformation. Furthermore, because new products and software are developed and implemented at a faster rate, businesses should be able to transform at the same rate and adapt to continuous, abrupt, and rapid change. Additionally, organizations should also enable employees with the flexibility and freedom to work on any device, at any time. Based on the abovementioned challenges, the digital transformation in action framework is presented in Fig. 2.9.

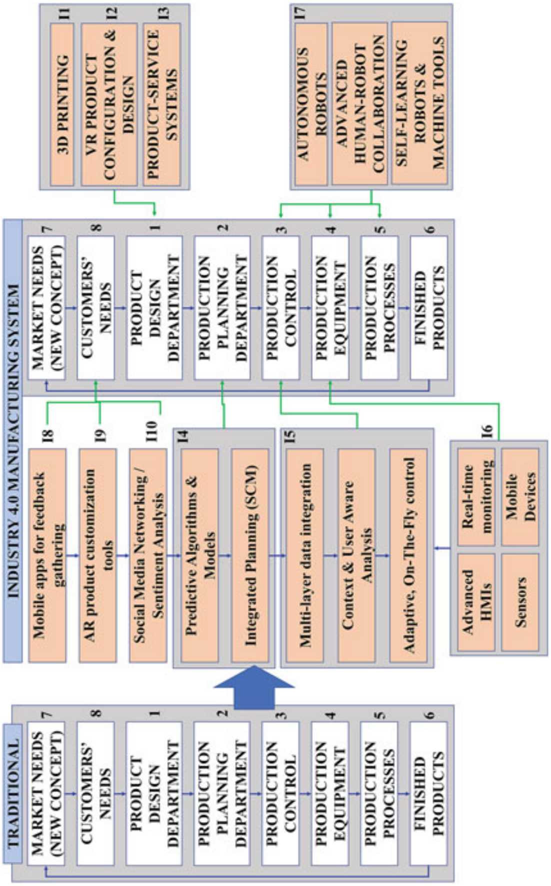


Fig. 2.8 Traditional manufacturing system vs. digitalized manufacturing system towards Industry 4.0

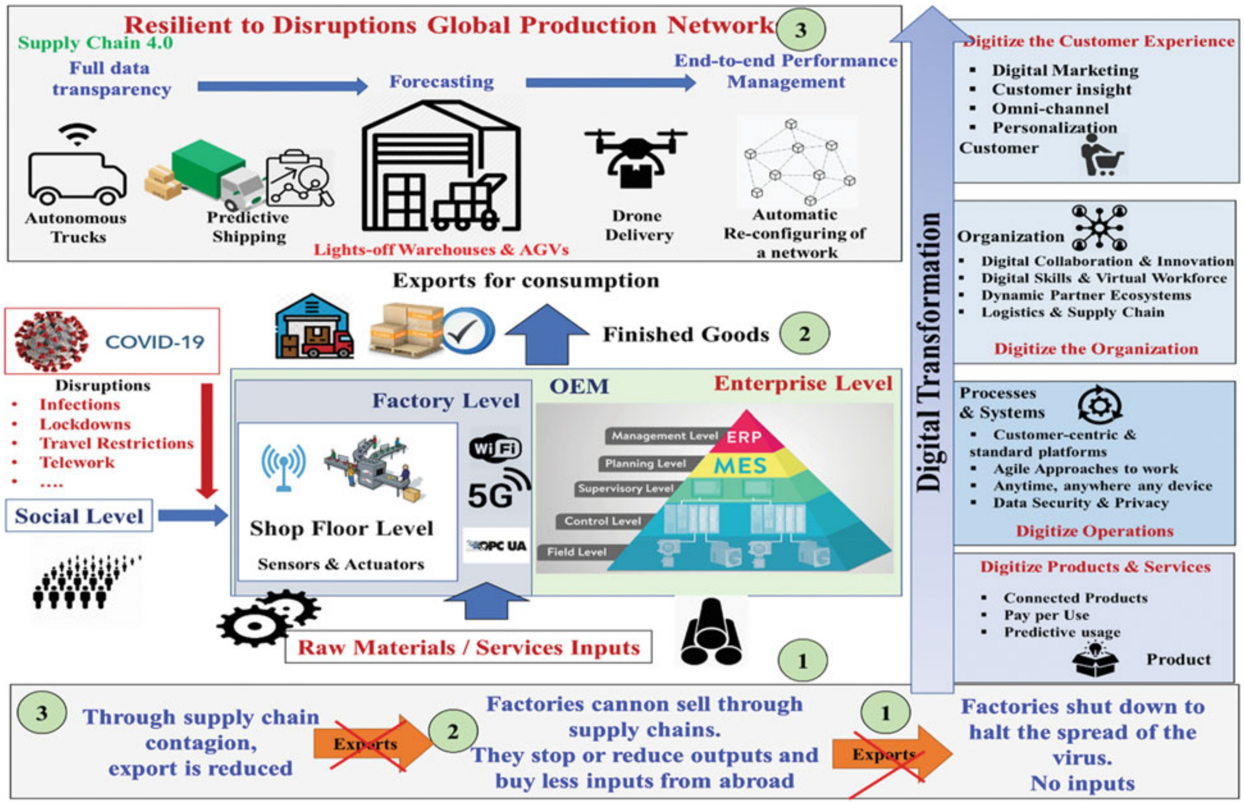


Fig. 2.9 Proposed framework for Digital Resilient Cloud-Based Supply Chains

2.5 Discussion and Outlook

2.5.1 Impact of COVID-19 Disruption on Smart Manufacturing

During the Post COVID-19 era, the global smart manufacturing market is expected to grow from USD181.3 billion in 2020 to USD220.4 billion by 2025, representing a 4.0% compound annual growth rate (CAGR). In comparison to the pre-COVID-19 assessment, the 2020 forecast is down 16%. The increasing demand for smart manufacturing products and solutions propelled by COVID-19, the importance of digital twin in maintaining operations within the manufacturing ecosystem, and the emerging and expanding role of collaborative robots in the healthcare and manufacturing sectors are all factors driving the growth of the smart manufacturing market.

Coronavirus has been first appeared in Wuhan, China, where many of the factories that supply parts, components, and semi-finished products to various manufacturing units around the world are located. Thus, that region was placed under lockdown for about 2 months to prevent the virus from spreading. Manufacturing units were closed and unable to produce any products during these months. This had a knock-on effect throughout the world's manufacturing facilities, causing the entire supply chain to break down. The following manufacturing units are the most affected (Market Research Report, 2020):

- Those who work on a Just-in-Time Model (JIT), in which raw materials are needed exactly when they are needed
- Those who rely entirely on China for raw materials, semi-finished goods, and other goods

2.5.2 Supply Chain Lessons Learned from COVID-19

It has been more than 2 years since the start of the COVID-19 global pandemic, which proved to be a challenging test for global supply chains. It began with medical device manufacturers facing an unprecedented surge in demand at the beginning of 2020, and gradually expanded to other sectors such as the automotive industry, which is currently experiencing semiconductor chip shortages. Learning from the supply chain challenges that businesses faced during the worst days of pandemic, is critical to prepare for future shocks/disruptions.

In a crisis like COVID-19, the role of Industry 4.0 becomes even more critical. Stakeholders who use digital solutions are better positioned to weather the storm because they moved faster and farther during the crisis than their competitors. Following LaBerge et al. (2020) report, 93% of manufacturing and supply-chain executives say they will focus on supply-chain resilience, and 90% say they will invest in talent for digitization.

2.5.3 Flexible Supply Chain

In times of disruption, a flexible supply chain can assist businesses in quickly adapting operations. Production can respond to changes in demand, customization requirements, changes in product design, and alternative supply sourcing. Furthermore, flexible supply chains can employ modularity at both the design and organizational levels, preventing the failure of a single component from affecting the entire system. Product designs embed coordination and lose coupling while reducing costs and improving response time by standardizing components and interfaces between components. This is a critical strategy for businesses that rely on single-source sourcing for critical components or have major suppliers concentrated in a specific geographic area.

2.5.4 The Importance of a Supply Chain with Revenue Assurance

When a company has to choose between efficiency and resilience, rethinking how they evaluate their suppliers is a must-have discussion. Companies can prepare to respond in times when their competitors are struggling by considering additional variables such as quality cost, lead time, technological value, and logistics costs into their sourcing strategies. However, while these measures improve supply chain resilience, they may do so at the expense of efficiency, necessitating a review of inventory policies or sourcing strategies by businesses.

2.5.5 The Importance of a Visible Supply Chain

Creating a visible supply chain begins with identifying all partners involved, determining critical components, and determining the source of supply. Most companies have traditionally limited supply chain mapping to tier-1 suppliers, underestimating the impact of a tier-2 or tier-3 supplier disruption. As such, Dun and Bradsteed (2020) estimated that at least 5 million companies, including nearly all of the Fortune 1000, had one or more tier-2 and tier-3 suppliers in the Wuhan region during the COVID-19 pandemic. Mapping necessitates not only a thorough understanding of a company's own supply chain, but also an understanding of industry competitors and adjacent industries, as the supply chain's long-term success is dependent on a collaborative business ecosystem.

2.5.6 The Importance of Logistics

As important as working with key suppliers is working with logistics and transportation partners. If the logistics capacity cannot be secured, having your goods manufactured by your suppliers is worthless. The technological and automotive industries have been affected in a major manner, as they rely heavily on air-cargo shipments, which have seen a massive drop in cargo capacity as a result of travel bans and unprecedented passenger flight cancellations. Furthermore, having real-time visibility of what is happening during the transit period, such as tracking time, airport congestion, or border closures, will allow supply chains to quickly react and anticipate disruptions by changing modes of transportation or rerouting.

2.5.7 The Importance of Supply Chain Risk Management

Companies that have a well-developed risk management strategy are better prepared to respond to disruptions, regardless of their severity. Even though many companies have implemented SCRM within their organizations, few truly understand where the risks lie and have limited their SCRM to a few reactive measures. Wherever possible, a proactive risk management approach would involve all functions of the supply chain and a dedicated multidisciplinary risk management team. Real-time event monitoring and supply chain visibility, multi-sourcing and buffer strategies, investment in critical element manufacturing capacity, evaluation of partners based on their SCRM plans, development of solid communication channels, and creation of awareness and transparency of the entire supply chain vulnerabilities are just a few examples of proactive strategies.

2.6 Conclusion

This chapter provides a literature review on the acceleration of digital transformation triggered by the pandemic as a catalyst in the adoption of Industry 4.0 technologies, as well as a conceptual framework for digital transformation and SMEs business model change. A scenario must be identified in order to assess the situation and evaluate current management practices in order to manage a crisis. The next step is to devise a strategy and assign roles to all parties involved. It is very beneficial to have a crisis management framework in place prior to the actual situation for a quick and structured response. The "New Normal" is the real challenge, because there can be many positive outcomes when dealing with a crisis. In this case, the COVID-19 pandemic facilitated digital transformation for many organizations and prompted top management to adopt innovative solutions in order to keep their operations running. It is critical that organizations continue the usage of these technologies and their integration into their daily operations after the pandemic is over. As a result, future steps will concentrate on the crisis response framework, as well as a service aimed at changing the current culture and smoothly establishing a "New Normal."

References

Abele, E., Elzenheimer, J., Liebeck, T., & Meyer, T. (2006). Globalization and decentralization of manufacturing. In A. I. Dashchenko (Ed.), *Reconfigurable manufacturing systems and transformable factories*. https://doi.org/10.1007/3-540-29397-3_1 Springer.

Acioli, C., Scavarda, A., & Reis, A. (2021). Applying Industry 4.0 technologies in the COVID–19 sustainable chains. *International Journal of Productivity and Performance Management.*https://doi.org/10.1108/IJPPM-03-2020-0137

Albukhitan, S. (2020). Developing digital transformation strategy for manufacturing. *Procedia Computer Science, 170*, 664–671. https://doi.org/10.1016/j.procs.2020.03.173

Anderson, J., Rainie, L., & Vogels, E. A. (2021). Experts say the 'new normal' in 2025 will be far more tech-driven, presenting more big challenges. *Pew Research Center, 18*.

Baghersad, M., & Zobel, C. W. (2021). Assessing the extended impacts of supply chain disruptions on firms: An empirical study. *International Journal of Production Economics, 231*, Article 107862. https://doi.org/10.1016/j.ijpe.2020.107862

Ballou, R. H. (2007). The evolution and future of logistics and supply chain management. *European Business Review*. https://doi.org/10.1016/j.ijpe.2020.107862

Budd, J., Miller, B. S., Manning, E. M., Lampos, V., Zhuang, M., Edelstein, M., … McKendry, R. A. (2020). Digital technologies in the public-health response to COVID-19. *Nature Medicine*, *26*(8), 1183-1192. DOI: https://doi.org/10.1038/s41591-020-1011-4

Chryssolouris, G. (2006). Manufacturing systems: Theory and practice. Springer Science & Business Media. https://doi.org/10.1007/0-387-28431-1

Corver, Q., & Elkhuizen, G. (2014). A framework for digital business transformation. *Cognizant Business Consulting Benelux*. https://www.cognizant.com/InsightsWhitepapers/a-framework-for-digital-business-transformation-codex-1048.pdf

Daud, A., & Zailani, S. (2011). Lean supply chain practices and performance in the context of Malaysia. *Supply Chain Management–Pathways for Research and Practice, 1*. https://doi.org/10.5772/15947

Davenport, T. H., & Redman, T. C. (2020). Digital transformation comes down to talent in 4 key areas. *Harvard Business Review*, 2–6. https://hbr.org/2020/05/digital-transformation-comes-down-to-talent-in-4-key-areas

Dolgui, A., Ivanov, D., Peron, M., & Sgarbossa, F. (2022). Expected trends in production networks for mass personalization in the cloud technology era. In *Design and operation of production networks for mass personalization in the era of cloud technology* (pp. 13–37). Elsevier. https://doi.org/10.1016/B978-0-12-823657-4.00003-8

Dolgui, A., Ivanov, D., & Rozhkov, M. (2020). Does the ripple effect influence the bullwhip effect? An integrated analysis of structural and operational dynamics in the supply chain. *International Journal of Production Research, 58*(5), 1285–1301. https://doi.org/10.1080/00207543.2019.1627438

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. https://doi.org/10.1080/00207543.2017.1387680

Dun and Bradsteed. (2020). *Business impact of the coronavirus*. Whitepaper. Retrieved March 15, 2022, from https://www.dnb.com/perspectives/supply-chain/coronavirus-business-impact.html

Financial Times. (2022). *China's new normal may be major export after pandemic*. https://www.ft.com/content/41f27e30-92c2-49f6-801a-231809f0fb87

Gross Domestic Product. (2020). *2nd Quarter 2020 (Advance Estimate) and Annual Update*. Bureau of Economic Analysis 2020. https://www.bea.gov/news/2020/gross-domestic-product-2nd-quarter-2020-advance-estimate-andannual-update

Gross, T., MacCarthy, B. L., & Wildgoose, N. (2018). Introduction to dynamics of manufacturing supply networks. *Chaos: An Interdisciplinary Journal of Nonlinear Science, 28*(9), 093111. https://doi.org/10.1063/1.5053669

Ham, Y. N., Johnston, R., & Riemer, K. (2003, December). Complexity and commitment in supply chain management initiatives. In *Proceedings of The Third International Conference on Electronic Business (ICEB 2003)*.

Heavin, C., & Power, D. J. (2018). Challenges for digital transformation–towards a conceptual decision support guide for managers. *Journal of Decision Systems, 27*(Suppl 1), 38–45. https://doi.org/10.1080/12460125.2018.1468697

Hosseini, S., Ivanov, D., & Dolgui, A. (2020). Ripple effect modelling of supplier disruption: Integrated Markov chain and dynamic Bayesian network approach. *International Journal of Production Research, 58*(11), 3284–3303. https://doi.org/10.1080/00207543.2019.1661538

Himmilman, A. T. (1996). Rationales and contexts for collaboration. Creating Collaborative Advantage, 19–43.

ILO. (2021). *ILO monitor: COVID-19 and the world of work* (7th ed., p. 2). International Labor Organization.

Ivanov, D. (2020a). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research Part E: Logistics and Transportation Review.*https://doi.org/10.1016/j.tre.2020.101922

Ivanov, D. (2020b). Viable Supply Chain Model: Integrating agility, resilience and sustainability perspectives – lessons from and thinking beyond the COVID-19 pandemic. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03640-6

Ivanov, D., & Das, A. (2020). Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: A research note. *International Journal of Integrated Supply Management, 13*(1), 90–102. https://doi.org/10.1504/IJISM.2020.107780

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak (2020). *International Journal of Production Research, 58*(10), 2904–2915. https://doi.org/10.1080/00207543.2020.1750727

Ivanov, D., & Dolgui, A. (2021a). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control 2021, 32*(9), 775–788. https://doi.org/10.1080/09537287.2020.1768450

Ivanov, D., & Dolgui, A. (2021b). OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: Managerial insights and research implications. *International Journal of Production Economics, 232*, 107921. https://doi.org/10.1016/j.ijpe.2020.107921

Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "Supply Chain-as-a-Service". *Transportation Research Part E: Logistics and Transportation Review, 160*, 102676. https://doi.org/10.1016/j.tre.2022.102676

Ivanov, D., Sokolov, B., & Dolgui, A. (2014). The ripple effect in supply chains: Trade-off 'efficiency-flexibility-resilience' in disruption management. *International Journal of Production Research, 52*(7), 2154–2172. https://doi.org/10.1080/00207543.2013.858836

Jackson, J. K. (2021). Global economic effects of COVID-19. *Congressional Research Service*. https://crsreports.congress.gov/

Kinra, A., Ivanov, D., Das, A., & Dolgui, A. (2020). Ripple effect quantification by supply risk exposure assessment. *International Journal of Production Research, 58*(19), 5559–5578. https://doi.org/10.1080/00207543.2019.1675919

KPMG International Cooperative. (2020). *Building supply chain resilience through digital transformation*. https://assets.kpmg/content/dam/kpmg/xx/pdf/2020/06/building-supply-chain-resilience-through-digital-transformation.pdf

Kusiak, A. (2018). Smart manufacturing. *International Journal of Production Research, 201856*, 508–517. https://doi.org/10.1080/00207543.2017.1351644

LaBerge, L., O'Toole, C., Schneider, J., & Smaje, K. (2020). *How COVID-19 has pushed companies over the technology tipping point—and transformed business forever*. McKinsey. https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/how-covid-19-has-pushed-companies-over-the-technology-tipping-point-and-transformed-business-forever

Lanza, G., Ferdows, K., Kara, S., Mourtzis, D., Schuh, G., Váncza, J., … Wiendahl, H. P. (2019). Global production networks: Design and operation. *CIRP Annals, 68*(2), 823–841. https://doi.org/10.1016/j.cirp.2019.05.008

Lanza, G., Peukert, S., & Steier, G. L. (2022). Latest advances in cloud manufacturing and global production networks enabling the shift to the mass personalization paradigm. In *Design and operation of production networks for mass personalization in the era of cloud technology* (pp. 39–77). Elsevier. https://doi.org/10.1016/B978-0-12-823657-4.00008-7

Lee, H., & Anderson, D. (2000). *The internet-enabled supply chain: From the "first click" to the "last mile"*. Retrieved December 9, 2015.

Lee, H. L., & Billington, C. (1995). The evolution of supply-chain-management models and practice at Hewlett-Packard. *Interfaces, 25*(5), 42–63.

Lewis, R. (2020). COVID-19 as a catalyst for digital transformation.. https://www.linkedin.com/pulse/covid-19-catalyst-digital-transformation-rajiv-lewis/?articleId=6661207244258062336

Lund, S., Madgavkar, A., Manyika, J., Smit, S., Ellingrud, K., Meaney, M., & Robinson, O. (2021). The future of work after COVID-19. *McKinsey Global Institute, 18*.

MacCarthy, B. L., Blome, C., Olhager, J., Srai, J. S., & Zhao, X. (2016). Supply chain evolution–theory, concepts and science. *International Journal of Operations & Production Management*. https://doi.org/10.1108/IJOPM-02-2016-0080

Market Research Report. (2020). *COVID-19 impact on smart manufacturing market*. https://www.marketsandmarkets.com/Market-Reports/covid-19-impact-on-smart-manufacturing-market-131502510.html

Matt, C., Hess, T., & Benlian, A. (2015). Digital transformation strategies. *Business & Information Systems Engineering, 57*(5), 339–343. https://doi.org/10.1007/s12599-015-0401-5

Meraihi, Y., Gabis, A. B., Mirjalili, S., Ramdane-Cherif, A., & Alsaadi, F. E. (2022). Machine learning-based research for COVID-19 detection, diagnosis, and prediction: A survey. *SN Computer Science, 3*, 286. https://doi.org/10.1007/s42979-022-01184-z

Mourtzis, D. (2020). Simulation in the design and operation of manufacturing systems: State of the art and new trends. *International Journal of Production Research, 58*(7), 1927–1949. https://doi.org/10.1080/00207543.2019.1636321

Mourtzis, D. (2022). The mass personalization of global networks. In *Design and operation of production networks for mass personalization in the era of cloud technology* (pp. 79–116). Elsevier. https://doi.org/10.1016/B978-0-12-823657-4.00006-3

Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2021a). Robust engineering for the design of resilient manufacturing systems. *Applied Sciences, 11*(7), 3067. https://doi.org/10.3390/app11073067

Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2021b). A survey of digital B2B platforms and marketplaces for purchasing industrial product service systems: A conceptual framework. *Procedia CIRP, 97*, 331–336. https://doi.org/10.1016/j.procir.2020.05.246

Mourtzis, D., & Doukas, M. (2015). On the configuration of supply chains for assemble-to-order products: Case studies from the automotive and the CNC machine building sectors. *Robotics and Computer-Integrated Manufacturing, 36*, 13–24. https://doi.org/10.1016/j.rcim.2015.02.009

Mourtzis, D., Doukas, M., & Psarommatis, F. (2012). A multi-criteria evaluation of centralized and decentralized production networks in a highly customer-driven environment. *CIRP Annals, 61*(1), 427–430. https://doi.org/10.1016/j.cirp.2012.03.035

Mourtzis, D., Doukas, M., Psarommatis, F., & Panopoulos, N. (2013). Design of multi-stage manufacturing networks for personalized products using metaheuristics. In A. Azevedo (Ed.), *Advances in sustainable and competitive manufacturing systems. Lecture notes in mechanical engineering*. https://doi.org/10.1007/978-3-319-00557-7_103. Springer.

Mourtzis, D., Fotia, S., Boli, N., & Vlachou, E. (2019). Modelling and quantification of industry 4.0 manufacturing complexity based on information theory: A robotics case study. *International Journal of Production Research, 57*(22), 6908–6921. https://doi.org/10.1080/00207543.2019.1571686

Mourtzis, D., Papakostas, N., Makris, S., Xanthakis, V., & Chryssolouris, G. (2008). Supply chain modeling and control for producing highly customized products. *CIRP Annals*, 57(1), 451-454. DOI: http://dx.doi.org/https://doi.org/10.1016/j.cirp.2008.03.106

O'Donovan, P., Bruton, K., & O'Sullivan, D. T. (2016). Case study: The implementation of a data-driven industrial analytics methodology and platform for smart manufacturing. *International Journal of Prognostics and Health Management, 7*(3) DOI: https://doi.org/10.36001/ijphm.2016.v7i3.2414

Paul, S. K., & Chowdhury, P. (2020). A production recovery plan in manufacturing supply chains for a high-demand item during COVID-19. *International Journal of Physical Distribution & Logistics Management*. https://doi.org/10.1108/IJPDLM-04-2020-0127

Peters, M. A. (2019). Technological unemployment: Educating for the fourth industrial revolution. In *The Chinese Dream: Educating the Future* (pp. 99–107). Routledge. https://doi.org/10.1080/00131857.2016.1177412

Pihir, I., Tomičić-Pupek, K., & Furjan, M. T. (2018). Digital transformation insights and trends. In *Central European Conference on Information and Intelligent Systems* (pp. 141–149). Faculty of Organization and Informatics Varazdin.

Porter, M. E. (2007). *The competitive advantage of nations: With a new introduction* (10th ed.). Palgrave.

Prince, T. (2000). *E-Commerce: Its impact on transportation, logistics, and supply chain management*.

Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso Wamba, S. (2020). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Annals of Operations Research*, 1–38. https://doi.org/10.1007/s10479-020-03685-7

Randhawa, G. S., Soltysiak, M. P., El Roz, H., de Souza, C. P., Hill, K. A., & Kari, L. (2020). Machine learning using intrinsic genomic signatures for rapid classification of novel pathogens: COVID-19 case study. *PLoS One, 15*(4), e0232391. https://doi.org/10.1371/journal.pone.0232391

Robinson, D. (2020). *NS Medical Devices. Manufacturing of key medical kit during Covid-19*. https://www.nsmedicaldevices.com/analysis/companies-ventilators-shortage-coronavirus/

Ruel, S., El Baz, J., Ivanov, D., & Das, A. (2021). Supply chain viability: Conceptualization, measurement, and nomological validation. *Annals of Operations Research*. https://doi.org/10.1007/s10479-021-03974-9

Russell R. S., Taylor, B. W., "Operations Management along the Supply Chain," 6th Edition, John wiley and Sons Ltd., Chichester, 2009.

Sawik, T. (2020). *Supply chain disruption management* (2nd ed.). Springer.

Sherman, E. (2020). 94% of the Fortune 1000 are seeing coronavirus supply chain disruptions: Report. *Fortune*. https://fortune.com/2020/02/21/fortune-1000-coronavirus-china-supply-chain-impact/

Solis, B., & Szymanski, J. (2016). *Six stages of digital transformation*. Altimeter Prophet.

Supply Chain & Operations. (n.d.). *Supply chain disruption*. Accenture. https://www.accenture.com/us-en/insights/consulting/coronavirus-supply-chain-disruption

Tang, C. S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics, 103*(2), 451–488. https://doi.org/10.1016/j.ijpe.2005.12.006

Trieut, R. (2020). *Autodesk-redshift. Companies help to fight COVID-19*. https://www.autodesk.com/redshift/manufacturing-covid-19/

Wee, D., Kelly, R., Cattel, J., & Breunig, M. (2015). Industry 4.0-how to navigate digitization of the manufacturing sector. *McKinsey, 58*, 7–11.

Wenz, L., Willner, S. N., Bierkandt, R., & Levermann, A. (2014). Acclimate—a model for economic damage propagation. Part II: A dynamic formulation of the backward effects of disaster-induced production failures in the global supply network. *Environment Systems and Decisions, 34*(4), 525–539. https://doi.org/10.1007/s10669-014-9521-6

Wood, M. D., Wells, E. M., Rice, G., & Linkov, I. (2019). Quantifying and mapping resilience within large organizations. *Omega, 87*, 117–126. https://doi.org/10.1016/j.omega.2018.08.012

World Economic Forum. (2020). *Innovation in meeting the ventilator demands*. https://www.weforum.org/agenda/2020/03/coronavirus-ventilators-covid19-healthcare/

Wuest, T., Kusiak, A., Dai, T., & Tayur, S. R. (2020). *Impact of COVID-19 on manufacturing and supply networks—The case for AI-inspired digital transformation*. Available at SSRN 3593540. https://doi.org/10.2139/ssrn.3593540

Yoon, J., Talluri, S., Yildiz, H., & Ho, W. (2018). Models for supplier selection and risk mitigation: A holistic approach. *International Journal of Production Research, 56*(10), 3636–3661. https://doi.org/10.1080/00207543.2017.1403056

Zeng, Y., & Xiao, R. (2014). Modelling of cluster supply network with cascading failure spread and its vulnerability analysis. *International Journal of Production Research, 52*(23), 6938–6953. https://doi.org/10.1080/00207543.2014.917769

Chapter 3
Collaborative Control, Task Administration, and Fault Tolerance for Supply Chain Network-Dynamics

Win P. V. Nguyen, Puwadol Oak Dusadeerungsikul, and Shimon Y. Nof

Abstract The purpose of this chapter is to describe how the dynamic requirements and behaviors of supply chains and their associated complex challenges can be and have been addressed by the tools and protocols of the collaborative control theory, CCT. These tools and protocols have been developed, tested, and implemented by the PRISM Center at Purdue University and by other researchers and industries around the world. In particular, collaborative control and collaboration engineering are important for successful coordination of supply activities and interactions, due to the multiple parties involved in the supply processes and services, all subjected to disruption, errors, conflicts, and dynamic many changes. In this chapter, we describe key relevant research, methods, and tools and illustrate case studies of successful implementation.

Keywords Collaborative control theory (CCT) · Cyber collaborative protocols · Disruptions · Supply networks · Task administration protocols

3.1 Introduction

The effective design, control, and management of supply chains and supply networks require appropriate coordination of materials and information flows in and between the involved firms and enterprises under dynamic changes and disruptions

---

W. P. V. Nguyen (✉)
PRISM Global Research Network, and School of Industrial Engineering, Purdue University, West Lafayette, IN, USA
e-mail: nguyen41@alumni.purdue.edu

P. O. Dusadeerungsikul
Department of Industrial Engineering, Chulalongkorn University, Bangkok, Thailand
e-mail: puwadol.d@chula.ac.th

S. Y. Nof
PRISM Center and School of Industrial Engineering, Purdue University, West Lafayette, IN, USA
e-mail: nof@purdue.edu

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_3

(Nof et al., 2015; Zhong & Nof, 2020). While "supply chain" is the common business term for the supply of goods and services, "supply network" is often used for the engineering design of supply systems, including also supply of sensor signals, digital information, knowledge, and other infrastructure commodities. In both, however, the focus is on the design and optimization of networks and the management of network dynamics.

Modern supply chains and networks often leverage information and communication technology (ICT) and increasingly cyber intelligence and control together with collaboration engineering mechanisms. Their objective is to provide effective coordination and benefit from the many potential strengths of outsourcing and supply network agreements. In particular, collaborative control and collaboration engineering are pivotal for successful supply chain coordination, due to the multiple parties involved in the many supply processes, activities, and interactions, all subjected to errors, conflicts, and dynamic changes (Fig. 3.1).

The importance of collaboration engineering was recognized already in the previous century, and led to the development of CCT, Collaborative Control Theory since the beginning of this century (Nof et al., 2015; Nof, 2007). The essential role of collaboration engineering is further emphasized by the decentralized nature of networked decision-making in supply chains: The firms have their own interests and work to maximize their own profits and minimize their own risks (Reyes Levalle, 2018). Collaboration engineering is also beneficial to the handling of supply chain disruptions (Reyes Levalle & Nof, 2015a). Such disruptions can have propagating/ripple effects if left unchecked, causing severe damages along the

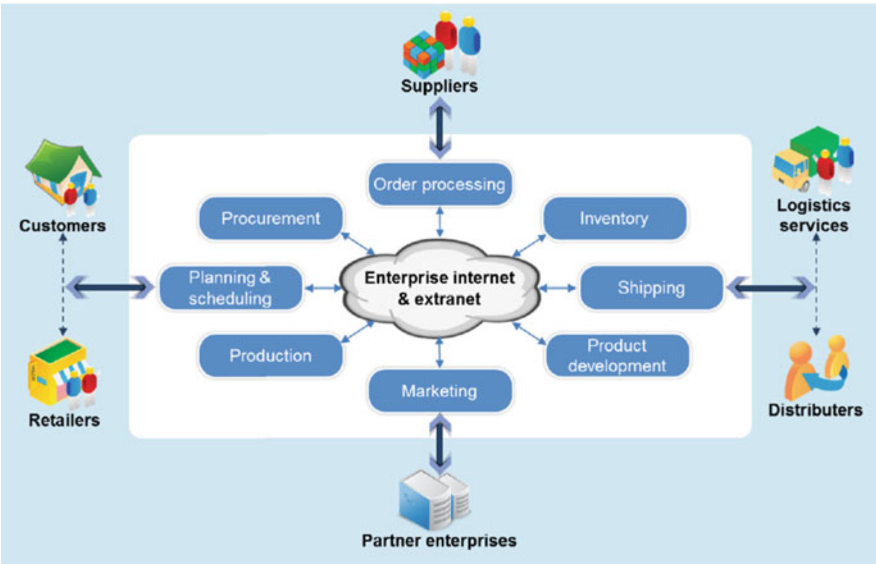


Fig. 3.1 Supply chain involved parties, processes, and activities (from Nof et al., 2015)

supply chain (Hosseini et al., 2019, 2020; Hosseini & Ivanov, 2020, 2021; Dolgui & Ivanov, 2020, 2021; Burgos & Ivanov, 2021). Many advanced supply chain resilience methods require the involved parties to participate in information sharing protocols and collaborative protocols to prepare against disruptions (Reyes Levalle & Nof, 2017). Collaboration engineering also finds applications in other supply chain processes and activities: security (Tkach et al., 2017), information sharing (Yoon et al., 2011), supplier selection (Seok & Nof, 2018), resource distribution (Scavarda et al., 2017), contingent multi-sourcing (Seok et al., 2016), demand and capacity sharing (Yoon & Nof, 2010; Seok & Nof, 2014), and the administration of collaborative tasks (Ko & Nof, 2010, 2012).

In this chapter, key collaborative control and collaboration engineering principles and methods relevant to supply chain networks dynamics are introduced and presented:

- Collaborative fault tolerance and resilience by teaming to enhance supply network resilience
- Collaborative demand and capacity sharing protocols
- Task administration protocols
- Collaborative response to disruption propagation framework
- Early detection, diagnosis, and treatment relevant to agricultural supply chains
- And cyber collaborative control, optimization, and harmonization of smart warehouse

The collaborative control principles and protocols discussed in this chapter as relevant to supply chain networks control are summarized in Table 3.1.

3.2 Collaborative Fault Tolerance and Resilience by Teaming Framework for Collaborative Supply Networks

The beginning of the twenty-first century has seen major supply chain disruptions, from the 2011 Japanese tsunami of 2011 that severely affected the auto industry to the 2011 Thailand's flood that disrupted the global hard drive supply. COVID-19 pandemic is a more recent and still ongoing disruption of supply (Dolgui & Ivanov, 2020, 2021). These major disruptions highlight the need for supply chain and network resilience (Hosseini et al., 2019; Chopra & Sodhi, 2014). Although supply network (SN) managers and executives appreciate the necessity of supply network resilience, the costs of supply network resilience implementation must be weighed against operational efficiency. The disruptions also tend to have a rippling effect along the supply network parties, which means an impact in one area can ripple to others (Zhong & Nof, 2020; Hosseini et al., 2019, 2020; Hosseini & Ivanov, 2020, 2021; Dolgui & Ivanov, 2020, 2021; Burgos & Ivanov, 2021; Ghadge et al., 2021; Ivanov et al., 2017). The disruptions are in contrast to recurrent risks such as demand fluctuations and delivery variability, which are typically handled by

Table 3.1 Summary of collaborative control principles relevant to supply chain networks control

Collaborative control principle	Some relevant methodologies	Sample case studies
Collaborative fault tolerance and resilience by teaming	Resilience by teaming framework. Team formation and re-configuration protocols for sourcing, distribution. Flow control protocols for sourcing/internal/distribution flows.	Production network and delivery network (Reyes Levalle & Nof, 2015a, 2015b)
Collaborative demand and capacity sharing	Demand sharing protocol. Capacity sharing protocol. Demand and capacity allocation protocol. Best-matching protocol.	Collaborative supply network (Yoon & Nof, 2010; Seok & Nof, 2014; Moghaddam & Nof, 2014)
Task administration protocols	Task requirement analysis protocol. Shared resource allocation protocol. Synchronization and time-out protocol.	Collaborative manufacturing and testing systems (Nof et al., 2015; Ko & Nof, 2010, 2012), facility sensor network (Nof et al., 2015; Ko & Nof, 2012), multi-sensor supply network security (Tkach et al., 2017; Tkach & Edan, 2020)
Collaborative response to disruption propagation and dynamic lines of collaboration	Collaborative response to disruption propagation framework. Propagation-restraining analysis. Network-based resource allocation protocols.	Repair of production capacity in manufacturing networks (Nguyen & Nof, 2018), dynamic repair of CPSs (Nguyen & Nof, 2019, 2020; Nguyen, 2020), detection of unknown disruptions in CPSs and agricultural greenhouses (Nguyen, 2020; Nguyen et al., 2021), water supply network (Zhong & Nof, 2015, 2020; Zhong, 2016)
Early detection, diagnosis, and treatment	Agricultural CPS design framework. Collaborative control protocol for early detection.	Food supply chain security (via agricultural robotic systems) (Guo et al., 2018; Dusadeerungsikul & Nof, 2019, 2021)
Cyber collaborative control, optimization, and harmonization	Collaborative requirement planning with optimization and harmonization.	Smart warehouse (Dusadeerungsikul et al., 2021)

good supply network management practices (Chopra & Sodhi, 2014). Compared to recurrent and normally anticipated risks, disruptions tend to have lower likelihood of occurrence, but are high impact, unpredictable, and thus difficult to forecast and prepare for. The potentially severe consequences of a direct disruption and the rippling effect from a related disruption mean that enterprises and firms must design and prepare their supply network appropriately.

The existence of disruptions raises the concern of supply network resilience (SNR) (Hosseini et al., 2019). SNR refers to the capability of a supply network to withstand, adapt, and recover from disruptions to normal operations, meeting customer demand and maintaining profitability. In the past few years, SNR has become an increasingly important concern for both industry and academia. Amongst other many methodologies and approaches, the Resilience by Teaming (RBT) framework has emerged as an approach that employs collaborative control theory and collaboration engineering principles to enable and augment SNR (Reyes Levalle, 2018; Reyes Levalle & Nof, 2015a, 2015b, 2017).

The RBT framework originates from the Collaborative Fault Tolerance (CFT) or Fault Tolerance by Teaming (FTT) Collaborative Control Theory (CCT) principle (Nof, 2007), which states that a team of weaker agents can outperform a single powerful agent by employing smart collaboration. The RBT framework is further enhanced by the situation awareness enabler from the Conflict and Error Detection and Prognostics principle of the CCT (Chen & Nof, 2012a, 2012b). The RBT framework is distinct from other SNR methodologies and approaches in the literature by forming and coordinating fault-tolerant teams of supply network agents to leverage their collaborative capabilities and collaborative tasks. In this section, a summary of the RBT framework is presented. The details of the formalism, task administration protocol design, and applications of the RBT framework can be found in Reyes Levalle (2018).

3.2.1 The RBT Formalism

The RBT framework establishes the formalism of the entities involved in this problem context. The SN agent a is defined as an autonomous entity with self-interests and has internal resources R_a that can process inputs into outputs. An SN agent a is also governed by a set of control protocols CP_a that governs the collaboration between its internal resources as well as the interactions with other agents.

Two types of SN links are defined. A flow link $\mathrm{fl}_{i \to j}$ connects the internal resources of agent i and j, enabling the flow from i to j, with every flow link having a set of time-dependent attributes $\Omega[\mathrm{fl}_{i \to j}]$ (e.g., capacity, status) that describe the interaction between the two agents at time t. A communication link $\mathrm{cl}_{i \to j}$ connects the control protocols of SN agents i and j, and also has a set of time-dependent attributes $\Omega[\mathrm{cl}_{i \to j}]$ similar to flow link. Each link has a service level agreement $\mathrm{SLA}_{i \to j}$ that defines the valid limits and ranges of the link. The quality of service provided by i to j is defined as $\mathrm{QoS}_{i \to j}$ (Eq. 3.1), with the accompanying function f to be defined based on the problem context.

$$\mathrm{QoS}_{i\to j} = f\left(\mathrm{SLA}_{i\to j}, \Omega\left[\mathrm{fl}_{i\to j}\right], \Omega\left[\mathrm{cl}_{i\to j}\right]\right) \tag{3.1}$$

The SN is then defined as a set of SN agents $A = \{1, \ldots, a\}$, the set of flow links FL, and the set of communication links CL. The SN agents are further categorized as source agents (those without input flow links) (Eq. 3.2), sink agents (those without output flow links) (Eq. 3.3), and kernel agents (those with at least one input and output flow link) (Eq. 3.4) (Reyes Levalle, 2015).

$$A^I = \{a \in A | \nexists \mathrm{fl}_{i\to a} \in \mathrm{FL}, i \in A\} \tag{3.2}$$

$$A^O = \{a \in A | \nexists \mathrm{fl}_{a\to i} \in \mathrm{FL}, i \in A\} \tag{3.3}$$

$$A^K = \left\{a \in A | a \notin A^I \wedge a \notin A^O\right\} \tag{3.4}$$

The goal of the SN is to provide the sink agents with sufficient QoS based on their SLA with the source agents and kernel agents. With the definitions established, SN formation can be formalized as the addition/removal of new/existing agents and links into the SN. SN re-configuration is defined as the addition/removal of links in the existing SN without adding/removing agents.

The advantage of the RBT formalism of SN is that the physical, digital, and service SNs can be conceptualized and modeled. For example, sensor networks involve agents generating, storing, transmitting, transforming, and receiving signals (Reyes Levalle, 2015). Similarly, physical SNs involve agents performing similar processes with physical products. Notably, digital and cyber service SNs can perform similar processes except storing physical flow, when compared with physical and cyber-physical SNs.

3.2.2 The RBT Framework

The RBT framework (Fig. 3.2) has two network-level activities (situation awareness and agent-agent negotiation) and two agent-level activities (design and operation).

At the network level, situation awareness is enabled by requiring each SN agent to share information (while preserving privacy) with each other. Situation awareness also requires SN regulators (a special type of agent) to collaborative detect topology and agent interaction vulnerabilities while ensuring fairness. For example, government agencies could be one example of SN regulator.

The second network-level activity is agent-agent negotiation. This activity includes the strategic decisions made among agents: deciding topological require-

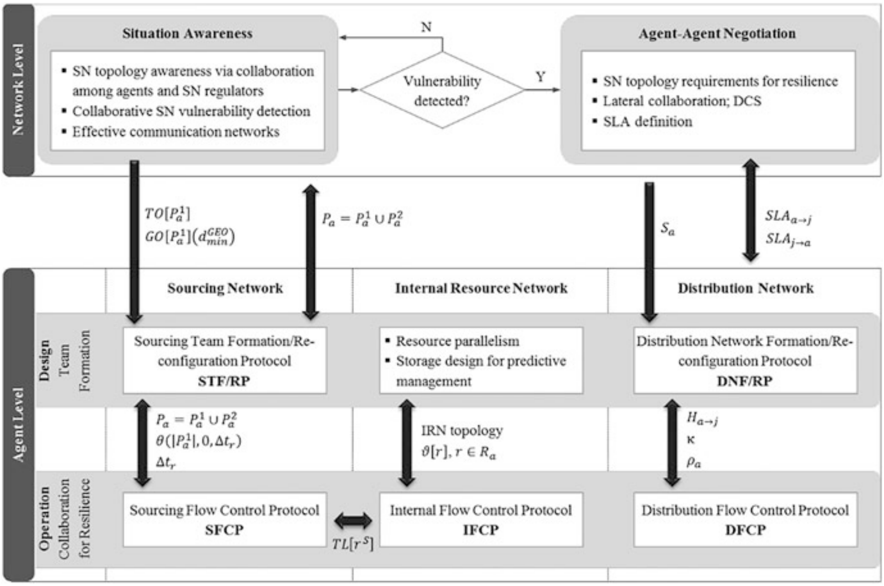


Fig. 3.2 The Resilience by Teaming (RBT) framework (from Liu & Nof, 2004)

ments, sharing decisions for excess flow demand and internal capacity, and defining service level agreements. The objective of this activity is to augment both agent-level and network-level performance and resilience.

The first agent-level activity is the team formation/design decision, which utilizes network-level information and context to design the teams. This activity consists of two agent-level team design protocols. The first protocol is called the Sourcing Team Formation/Re-Configuration Protocol (STF/RP). The STF/RP forms teams of weak sourcing agents to supply primary flow as well as share flow with other weak agents to overcome supply deficiency. The second protocol is the Distribution Network Formation/Re-Configuration Protocol (DNF/RP). The DNF/RP evaluates delivery network conditions to define delivery teams to provide disruption protection and minimize delivery costs. The other component of team formation/design decision is the application-specific internal resource network design, which strives to lower operational costs while overcoming disruptions if possible.

The second agent-level activity is the team operation decision, consisting of three protocols. The Sourcing Flow Control Protocol (SFCP) is used to regulate ordering from the sourcing teams (both primary and secondary) as defined by STF/RP. The replenishment parameter Δt_r decides the frequency of replenishment. The Internal Flow Control Protocol (IFCP) is used to manage internal resources R_a to maintain steady input-to-output productivity and to minimize variability from disruptions. The IFCP also affects SFCP, due to storage parameters influencing the replenishment parameters. The Distribution Flow Control Protocol (DFCP) regulates flow delivery from a to its successors. The DNF/RP design decisions influence the DFCP of each agent, thereby providing network resilience against disruptions.

3.2.3 STF/RP, SFCP, DNF/RP, and DFCP

The STF/RP recommends the formation/re-configuration of two sourcing team for each agent a: the primary sourcing team P_a^1 and the secondary sourcing team P_a^2. The primary sourcing team for each agent is selected to try to fulfill demand levels at different levels of variability, while considering delivery time variability and topological correlation. Topological correlation is the phenomenon where two or more agents share the same sources, which can lead to a disrupted source agent affecting multiple agents it is supposed to supply to. The secondary sourcing team, on the other hand, is supposed to address a small fraction of the sourcing needs of agent a as well as emergency delivery. Following SCFP, the secondary team should include as many members as possible to ensure the structure is not activated often.

The SFCP follows four guidelines to foster network resilience. The first guideline is the teaming of P_a^1 of each agent a to ensure delivery time Δr. The second guideline is to exchange delivery status information to increase congestion and disruption awareness. The third guideline is the prompt communication of disruptions from $i \in P_a^1$ to a so that recovery actions can be initiated. The fourth guideline is to allow overlapping deliveries to reduce negative consequences of competition while increasing protection against disruptions. When an agent a detects a gap in sourcing that P_a^1 cannot cover, an emergency bid is called for P_a^2 to address the sourcing gap.

The DNF/RP establishes a delivery network that allows agents to act as intermediate nodes for one agent to send its flow to another distant agent. An important requirement is that DNF/RP must ensure at least one path exists for all pairs of agents. Each agent i considers all possible paths from i to another agent j and requests estimations of processing rate and flow time from the intermediate nodes. Then, three measures of slack time, delivery cost, and flexibility are computed for each path. DNF/RP uses fuzzy logic to select the best path based on the aforementioned three measures. The DFCP operates by using the best path set by DNF/RP, but reevaluates this path at each intermediate node to account for congestions and disruptions.

3.2.4 RBT Case Studies

In this section, two case studies using the RBT framework are discussed. The first case study concerns an unreliable tissue paper production network. The second case study concerns distribution networks subjected to congestions and disruptions.

In the first case study (Fig. 3.3), (Reyes Levalle & Nof, 2015a, 2015b), a production network consists of agents that can be individually subjected to process

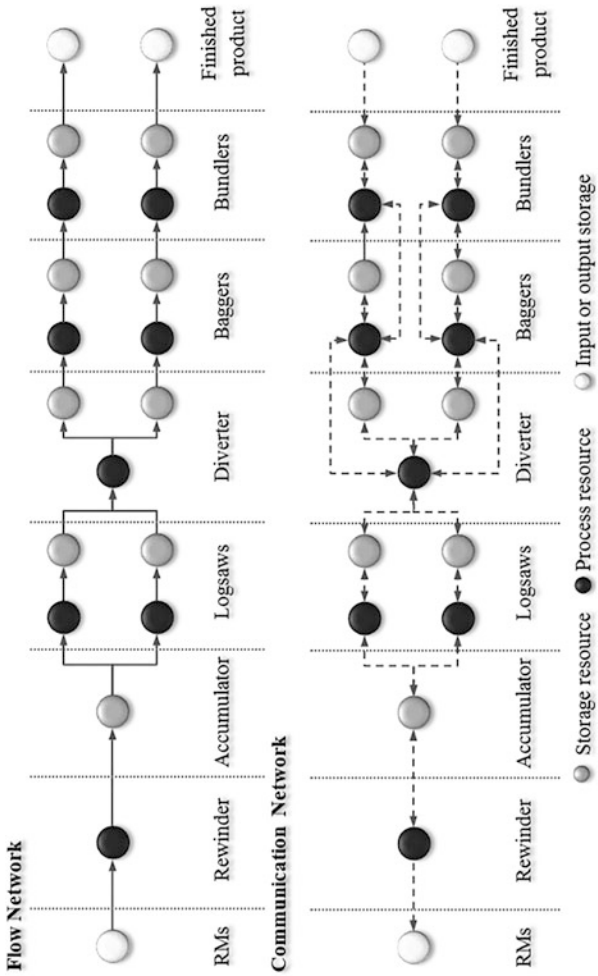


Fig. 3.3 Flow and communication networks of the tissue converting line (from Liu & Nof, 2004)

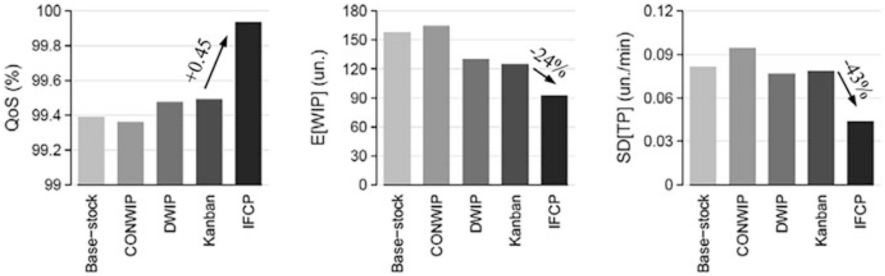


Fig. 3.4 Comparison of IFCP protocols (from Reyes Levalle, 2015)

failures, resulting in reduced production capacity. In this case study, the IFCPs are tailored to the real-world tissue paper production network application. This consists of optimal internal resource network (IRN) configurations, forecast of likely-to-occur failures in the near future, and teaming rules to respond to disruptions. The optimal IRN configurations allow the maximization of throughput under different resource conditions. The failure forecast utilizes the shared historical data of past failures amongst the agents to help prepare for near future disruptions. The teaming rules then utilize the near future failure information to adjust the process parameters of the agents upstream and downstream. Numerical experiments were performed to evaluate the effectiveness of IFCP, compared to four other control protocols: base-stock, constant WIP, dynamic WIP, and Kanban. The results indicated that IFCP yields statistically significant 43% reduction in throughput variance as well as 24% reduction of work-in-process inventory (Fig. 3.4).

In the second case study (Reyes Levalle & Nof, 2015a, 2015b), a small parcel delivery network is subjected to congestion and disruptions. In this case study, three types of agents are identified: distribution centers, docking facilities, and destinations. Using RBT formalisms, the distribution centers are equivalent to source agents, destinations are equivalent to sink agents, and docking facilities are equivalent to kernel agents. Following DNF/RP, the paths amongst all agents are computed, and fuzzy logic is applied to compute the scores for each path. DFCP is then applied and compared with two other routing protocols: shortest-time and lowest-cost. Under congestion and disruptions, DFCP provides statistically significant better on-time delivery compared to lowest-cost routing while providing lower cost than shortest-time delivery, especially at higher congestion level (Fig. 3.5).

For both case studies, the SN formation and re-configuration dynamics are also explored (Reyes Levalle & Nof, 2015a). Each non-source agent can reselect their suppliers according to a predetermined strategy. Four supplier selection strategies were implemented: single supplier to minimize cost; single supplier to maximize QoS; one supplier to minimize cost and one supplier to increase QoS; and the RBT approach that selects several low-cost suppliers to yield high QoS. Concurrently with supplier selection, each non-sink agent also submits bids to its potential

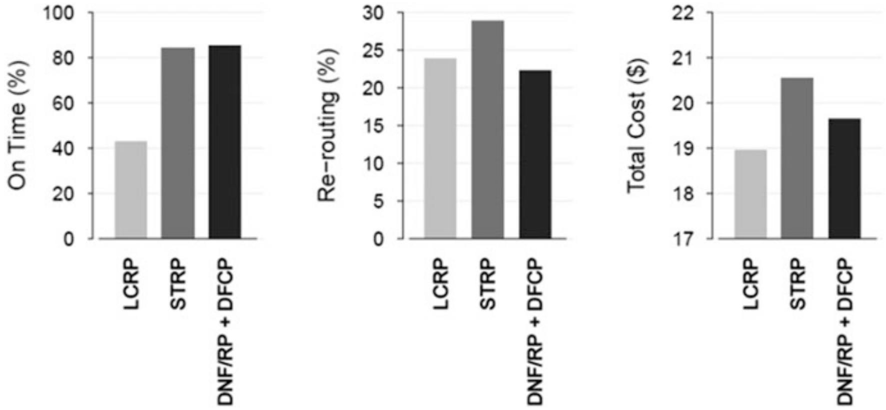


Fig. 3.5 Comparison of DFCP protocols (from Reyes Levalle, 2015)

customers. Depending on system status, SN agents may follow RBT protocols to re-configure their set of suppliers and set of customers to satisfy their own interests. Experimental results indicated that when at least 20% of the agents in the SN employ RBT protocols, the QoS loss from random and targeted disruptions are reduced. When compared to the case without RBT agents, the cases with RBT agents have lower disruption recovery costs.

3.3 Collaborative Demand and Capacity Sharing

In modern enterprises, the dynamic changes of customer demand patterns are inevitable, necessitating enterprise and multi-enterprise collaboration. In a supply chain network, excess demands can be fulfilled by implementing Demand and Capacity Sharing Protocols (DCSP) (Yoon & Nof, 2010, 2011). Specifically, non-competing enterprises of the same horizontal layer can opt to share their available capacities to fulfill each other's unfulfilled demands and orders, ultimately improving revenues and profits (Seok & Nof, 2014). Even though firms of the same supply network tier produce/provide similar types of products and services, they could serve different industries, markets, and geographical regions (Yoon & Nof, 2010; Seok & Nof, 2014). The improved mutual profits are mainly due to increased utilization and are enabled by resource sharing, information sharing, and responsibility sharing (Moghaddam & Nof, 2014).

Collaborative demand and capacity sharing involve the firms establishing collaborative networks with each other. This involves the collaborative network establishing ground rules and information sharing capabilities (Yoon & Nof, 2010). The Demand Sharing Protocol (DSP) is triggered upon the receival of new customer orders that cannot be fulfilled by the enterprise that received the order.

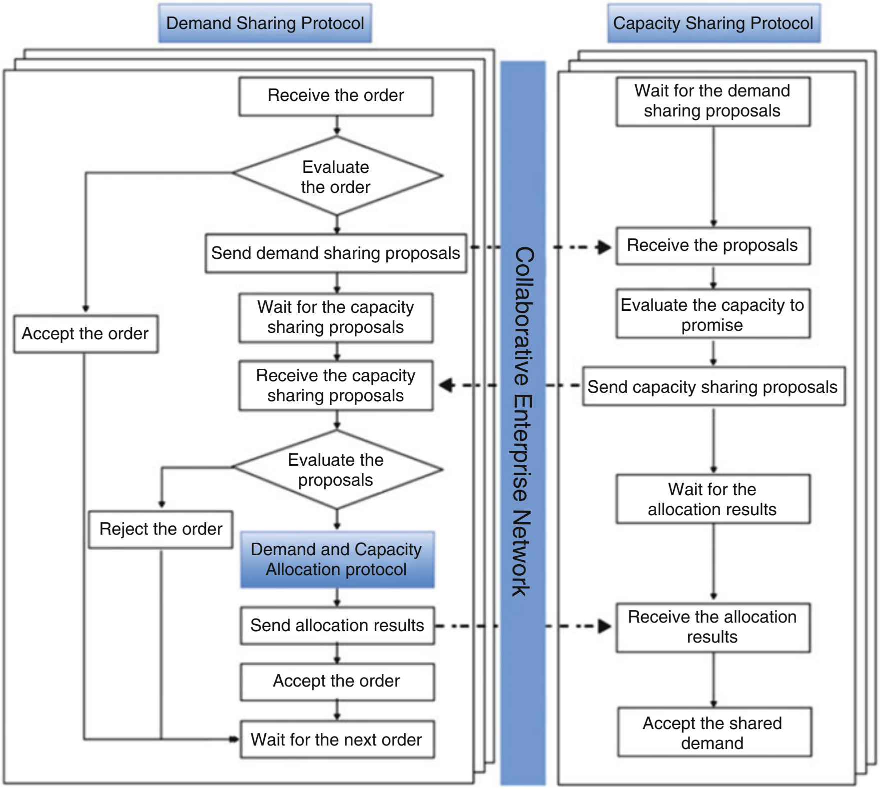


Fig. 3.6 Illustration of demand and capacity sharing protocols (from Yoon & Nof, 2010)

Demand sharing proposals are sent to the collaborating enterprises, activating the Capacity Sharing Protocol (CSP). Following CSP, each enterprise evaluates its own capacity to fulfill the order, then sends the capacity sharing proposals back to the requesting enterprise. The capacity sharing proposal is a promise (within a reasonable timeframe) to fulfill a certain portion of the received shared order. Then, The Demand and Capacity Allocation Protocol (DCAP) is activated to portion and allocate the orders to the collaborating enterprises. An example of DSP and CSP is depicted in Fig. 3.6. The DCAP can be implemented in a centralized manner (by the requesting enterprise or another decision-making body) or in a decentralized (by reiterative negotiations) manner. Detailed examples are explained in the works of (Yoon & Nof, 2010; Seok & Nof, 2014; Moghaddam & Nof, 2014).

In Yoon and Nof (2010), DCAP is implemented with a fixed coordination cost per participant that is assumed to be the same across all firms. To minimize the total cost for the order, the capacity sharing proposals are sorted in descending order by capacity amount, and the participants are selected until the order is fulfilled. In (Yoon & Nof, 2010), DCSP was validated by numerical experiments with three collaboration modes: no collaboration, partial collaboration, and complete collaboration. The experiment results indicated that complete collaboration has the statistically significant highest order fulfillment rate across all levels of demand variability, but the lowest total profit at lower demand variability, and moderate total profit at higher demand variability. Partial collaboration was found to provide the highest total profit and moderate demand fulfillment rate across all levels of demand variability. In Seok and Nof (2013, 2014), DCAP is implemented with a bidding process together with selective long-term collaboration. The results also indicated that the design of DCSP and DCAP should consider fairness to maintain strong partnerships and relationships within the collaborative network.

In Moghaddam and Nof (2014), DCAP is implemented with the CCT Best-Matching Protocol and utilizes fuzzy mixed integer programming to find the optimal allocations. The mixed integer programming formulation minimizes the total costs from production, inventory, backorders, and DCSP coordination. Possibilistic programming is then employed to tackle demand variability. The addition of best-matching protocol allows the demand levels and capacity levels between customers and suppliers to be matched to minimize the coordination/collaboration cost. The addition of best-matching protocol further reduces total costs, increases demand fulfillment rate and resource utilization, and increases stability when facing demand variability. In Moghaddam and Nof (2016a), a real-time control mechanism is added to DCSP to harmonize the distributed operations in the face of uncertainty, unexpected developments, and disruptions in the supply network. An improved predictive best-matching protocol is developed to dynamically match orders to resources in real-time while considering the near future timeslots.

3.4 Task Administration Protocols for Handling Supply Network Dynamics

Task Administration Protocols, also known as cyber collaborative protocols, are an important mechanism of CCT, the collaborative control theory, discussed earlier in this chapter. In distributed networked systems where collaborative tasks are possible, desirable, and often critical to success, the allocation, scheduling, harmonizing and, in general, administrating the collaborative tasks become highly sophisticated. This increased sophistication is due to the increasing dynamicity and complexity of interactions among the supply networked parties. The increasing complexity calls for the development of advanced collaborative control mechanisms of which Task Administration Protocols (TAPs) are a part of (Nof et al., 2015; Ko & Nof, 2010, 2012).

TAPs are control protocols that can actively make decisions and trigger timely actions to improve coordinated performance. The control scope of TAPs includes the initiation, allocation, and monitoring of tasks. TAPs can find applications in the management of events, security, and disruptions in supply networks (Tkach et al., 2017), as well as other supply network task types that require and/or benefit from collaboration of agents. The general design and analysis of TAPs are provided in Ko and Nof (2010, 2012), can use abstract Petri Nets and other network models to specify the control details of TAPs. TAPs are developed and implemented competitively for different supply network functions and applications, as explained throughout this chapter. Yet there are three main functional types that are common to many TAPs.

In Ko and Nof (2010, 2012), a task T_i is defined as

$$T_i = \langle \mathrm{type}_i, \mathrm{qty}_i, \mathrm{dd}_i, v_i, \mathrm{PR}_i(t) \rangle \tag{3.5}$$

In Eq. (3.5), type_i denotes the class of T_i that requires a resource agent's skill, qty_i denotes the task amount that is needed from the resource agent, dd_i is the latest time that the task must be processed by a resource agent, v_i is the task value, and $\mathrm{PR}_i(t)$ is the priority of the task at time t.

The first functional type of TAP is the Task Requirement Analysis Protocol (TRAP). This protocol function is triggered upon arrival of new task at a task agent. TRAP identifies the task type, analyzes task requirements (such as due date, task dependencies, resources required). Then, the priority of the new task is calculated and the task is added to the task queue, which is reordered based on task priority.

The second functional type of TAP is the Shared Resource Allocation Protocol (SRAP). This protocol function is activated after TRAP to find the most appropriate resources for the tasks. Depending on the protocol setting, SRAP can assign resources based on cost-effectiveness, utilization, idle time, availability, and a combination thereof.

The third functional type of TAP is the Synchronization and Time-Out Protocol (STOP). This protocol function monitors all ongoing tasks (being processed by shared resources) based on a set of time-out conditions. If a condition is met, the task is preempted, halted and could be reworked, and the resource is removed from the task. In Ko and Nof (2012), three time-out conditions were identified. The first time-out condition is excessive resource occupation, which is caused by the shared resource being occupied beyond a certain threshold. This could be caused by unexpected and unforeseen circumstances. The second time-out condition is preemption by urgent task, which is activated upon receipt of a high-priority task. In this case, the shared resource assigned to a low-priority task could be time-outed to handle (be available to) the incoming high-priority task. The third time-out condition is adaptation and relaxation of task requirements, which reassigns task and shared resource allocation to find better matches and faster completion time.

Benefits of TAPs, as illustrated in the case examples in this chapter, include improved system reliability and resilience, improved throughput and task completion rate, and others. TAPs have been applied competitively and successfully to different production and service system contexts that are modeled and designed as supply networks, beyond the examples described in this chapter, for instance: the TestLAN collaborative manufacturing and testing systems (Nof et al., 2015; Ko & Nof, 2010, 2012), facility sensor network (Nof et al., 2015; Ko & Nof, 2012), and best-matching processes (Nof et al., 2015; Moghaddam & Nof, 2014, 2016b), multi-sensor supply network security (Tkach et al., 2017; Tkach & Edan, 2020).

3.5 Collaborative Response to Disruption Propagation

The production functions of modern supply chains and networks are often dependent on and/or deeply interconnected with cyber-physical production systems (Nguyen, 2020; Panetto et al., 2019). Therefore, disruptions in the cyber-physical production systems can lead to supply chain disruptions. Other supply chain functions such as transaction processing, information and communication technology, ERP, and collaboration platforms are also highly interconnected cyber-physical systems (CPSs).

Due to the complex interactions and the high interconnectedness of CPSs, disruptions occurring in one part of a CPS can propagate to other parts, causing widespread damages if left unchecked (Nguyen & Nof, 2019). The phenomenon of disruptions spreading from one part of a CPS to another part is often termed disruption propagation (Nguyen & Nof, 2019; Nguyen, 2020; Nguyen et al., 2021) or cascading failures (Zhong & Nof, 2015, 2020; Zhong, 2016; Zhong et al., 2014). In a highly interconnected CPS, disruption propagation not only further damages the CPS, it also further increases workload: information processing, decision-making, response allocation. The increased disruption response workload further reduces the effectiveness and/or the efficiency of response resource allocation, exacerbating the situation.

3.5.1 The CRDP Framework

The Collaborative Response to Disruption Propagation (CRDP) framework (Fig. 3.7) was developed to formalize the affected system (also called the client system), the response resources, and the disruption propagation (Nguyen, 2020). Significantly expanding upon the Dynamic Lines of Collaboration application to disruption handling in CPSs (Zhong & Nof, 2015, 2020; Zhong, 2016; Zhong et al., 2014), the CRDP framework investigates and formalizes the key components and interactions of the disruption propagation response problem (Nguyen & Nof, 2019; Nguyen, 2020). Following the CRDP framework, the affected system, called the client system, is modeled as a complex network, with each distinct component/subsystem modeled as nodes (Fig. 3.8).

Formally, the client system is defined as the set of nodes N, with each node $n \in N$ representing a component/subsystem of the client system that can be affected by disruptions. The disruptions can be represented as node attributes with values 0, 1, or between 0 and 1. Different disruption types can be defined, depending on problem contexts. In the simplest case, the binary disruption attribute $d(n, t) \in \{0, 1\}$

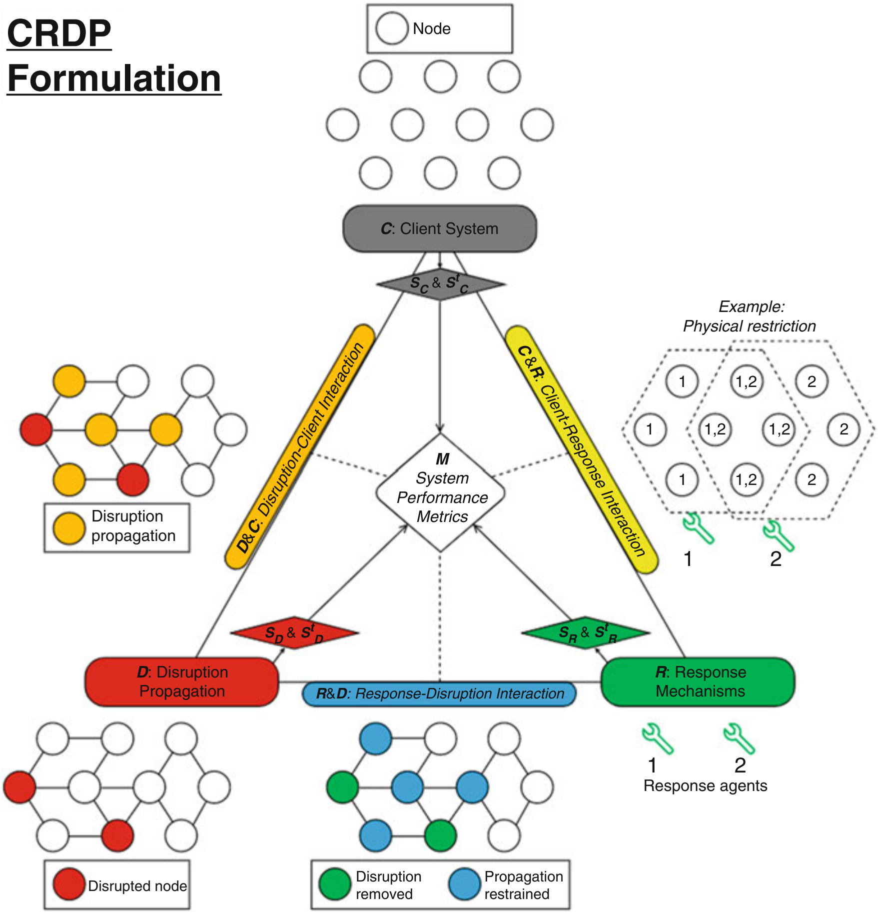


Fig. 3.7 CRDP framework (from Nguyen, 2020) for supply network of power, goods, foods, water, information, services, etc.

can represent the disruption status of node n at time t, with 0 representing the undisrupted status and 1 representing the disrupted status.

The edges, directed or undirected, would represent the potential disruption propagation directions from one node to another. If there exists a directed edge $e = (n_1, n_2)$ from node n_1 to node n_2, this means if node n_1 is disrupted, node n_2 can be disrupted. On the other hand, undirected edges represent the potential for disruptions to propagate in both directions, thus $e = \{n_1, n_2\} = (n_1, n_2) \cup (n_1, n_2)$.

The set of all the edges e is defined as E. The specific disruption propagation types and mechanisms depend on the problem context. One simple case: $\forall n_1, n_2 \in N : \exists\, e = (n_1, n_2) \in E : d(n_1, t) = 1 \rightarrow d(n_2, t + 1) = 1$. This means if node n_1 is disrupted at time t, node n_2 will become disrupted at time $t + 1$. However, more

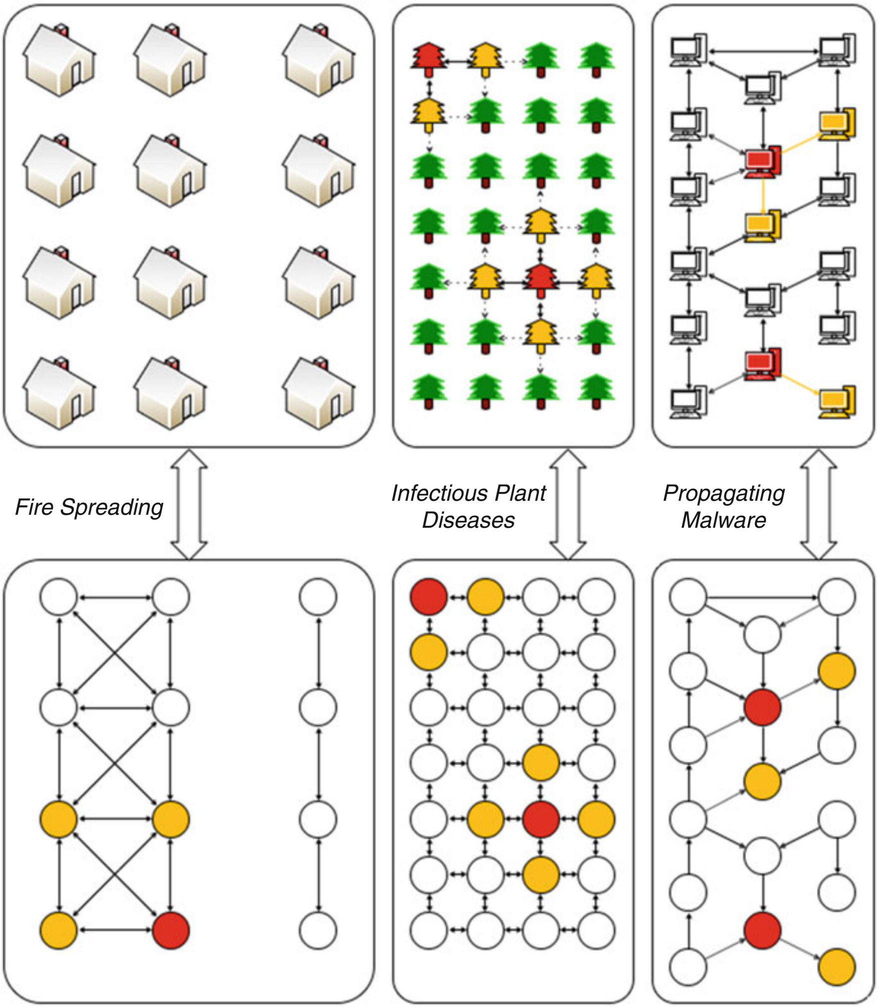


Fig. 3.8 Examples of disruption propagation network modeling (from Nguyen, 2020)

sophisticated modeling logic would be required to include response mechanisms behaviors as well as response-disruption interaction effects.

The complex network modeling enables situation awareness and complex network analysis, which can help anticipating the disruption propagation speed and patterns. In particular, centrality analysis can be performed (Zhong & Nof, 2015, 2020; Zhong, 2016; Zhong et al., 2014), including degree centrality C_D (Eq. 3.6), closeness centrality C_C (Eq. 3.7), and in-between centrality C_I (Freeman, 1978) (Fig. 3.9). The centrality equations provided below are examples with undirected edges. The notation $\text{spd}(n, n_j)$ is the shortest path distance from node n to node n_j,

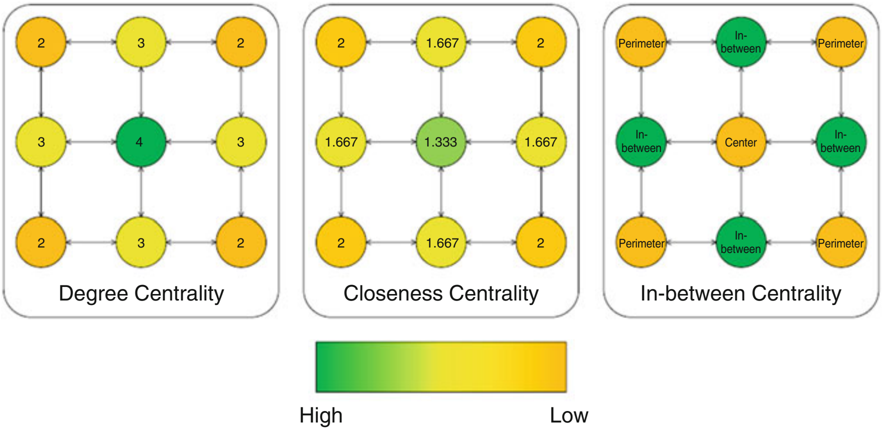


Fig. 3.9 Examples of different centrality measures: degree, closeness, and in-between

which can be computed with the Floyd-Warshall algorithm (Floyd, 1962).

$$C_{\mathrm{D}}(n) = \left|\left\{e = \left\{n_i, n_j\right) \in E | n_i \equiv n\right\}\right| \tag{3.6}$$

$$C_{\mathrm{C}}(n) = \frac{\sum_{n_j}^{N} \mathrm{spd}(n, n_j)}{|N|} \tag{3.7}$$

Against disruption propagation, response resources can be deployed to tackle the disruptions. The response types can include repair/recovery, prevention, and/or detection. The availability of response is often limited due to economic reasons. An important analysis and decision support of the CRDP research is the propagation-restraining effect (Nguyen & Nof, 2019; Nguyen, 2020). This effect was also leveraged by the Dynamic Lines of Collaboration principle to design the Activity-Based Priority collaboration protocol (Zhong & Nof, 2015, 2020; Zhong, 2016; Zhong et al., 2014). This effect means that the disruptions will not propagate if prevented, detected, or repaired. This effect is similar to how a fire does not spread if it is put out, or how plant diseases do not propagate if timely detected and treated. While often automatically beneficial, the propagation-restraining effect requires advanced analytical methodologies to be effectively utilized, ultimately improving recovery probability and reducing recovery time.

Utilizing the disruption propagation network modeling, the disruption propagation potentials of the different disrupted nodes are first calculated. Complex network analytics such as centrality analysis can be applied here to calculate the importance of the different nodes (Nguyen & Nof, 2018; Nguyen, 2020). Probability inference methods such as Bayesian network inference can also be employed in the case of disruption detection (Nguyen et al., 2021). The disruption propagation potentials should be calculated before disruptions occur (for strategic preparation) and updated real-time (for dynamic response). The capability of the available response resources is then analyzed, and the propagation-restraining analytics are then computed. The propagation-restraining effect was found to be highly beneficial in all the investigated cases of disruption repair, prevention, and detection. The propagation-restraining effect significantly reduces the damage to the CPS as well as the response workload, further reducing damages. Then, the response resources are allocated to tackle the disruptions.

3.5.2 The CRDP Case Studies

The design and analysis of disruption analytics and response resource allocation depend significantly on the specific problem context and application. The CRDP framework has been applied to several different applications and problem contexts: repair of production capacity in manufacturing networks (Nguyen & Nof, 2018), dynamic repair of CPSs (Nguyen & Nof, 2019, 2020; Nguyen, 2020), detection of unknown disruptions in CPSs and agricultural greenhouses (Nguyen, 2020; Nguyen et al., 2021), and strategic prevention of disruptions in CPSs (Nguyen, 2020; Freeman, 1978).

In the example of repair of production capacity in manufacturing networks (Nguyen & Nof, 2018), disruption status values are in $[0, 1]$, with directed weighted edges denoting production dependency relationships. Repair resources are deployed to remove the disruption status values over time, gradually restoring production capacity of the manufacturing network. In this problem, eight different node indices specific to network centrality, network flow, and network disruptions were developed. The node indices indicate the importance of a node to the overall network. For a selected node index type, repair resources are allocated based on the value of the selected node index (e.g., higher node index receives more repair resources).

In the example of dynamic repair of CPSs (Nguyen & Nof, 2019, 2020; Nguyen et al. 2019; Nguyen, 2020), disruption status values are in $\{0, 1\}$, with directed weighted edges denoting the time taken for disruption to propagate. Repair resources are deployed to remove the disruption status (returning from 1 to 0), with each repair taking a certain amount of time. Due to the limited number of repair agents, this scenario is similar to a race against time. If the disruptions are not timely handled, their propagation will overwhelm the repair agents, causing catastrophic damages to the affected system. In this example, the propagation-restraining effect was effectively utilized to design response protocols for the repair agents. In Nguyen and Nof (2019), the propagation-restraining effect was utilized to design allocation protocols, resulting in the minimizing neighboring disruption propagation (MNDP) protocol and minimize additional task workloads (MATW) protocol. Numerical experiments indicated that utilizing the propagation-restraining effect led to better recovery probability, recovery time, reduced CPS damages, and better resource usage. As shown in Fig. 3.10, the MNDP and MATW protocols

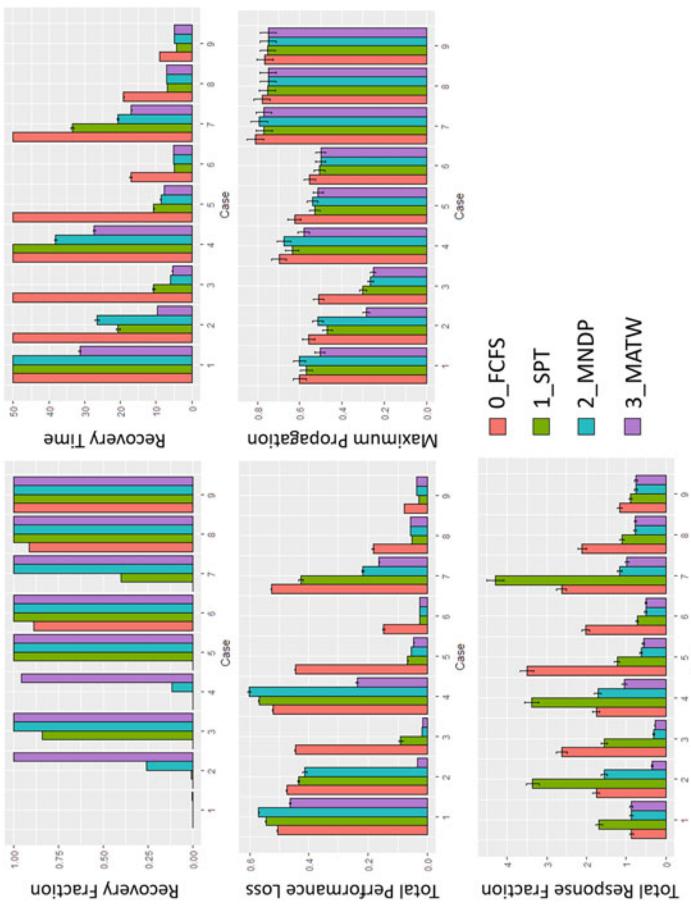


Fig. 3.10 Comparison of protocols in the disruption propagation repair case (from Nguyen & Nof, 2019)

outperform the baseline allocation protocols with statistical significance in all five performance measures.

In the example of detection of unknown disruptions in CPSs and agricultural greenhouses (Nguyen, 2020; Nguyen et al., 2021), the disruption status values are binary $\{0, 1\}$ and are not known to the operator in real-time unless the nodes are scanned. The scan results can be used together with the disruption propagation network modeling to infer the disruption status of the connected nodes. For example, if there is a directed edge from n_1 to n_2, and n_1 was found to be disrupted, then n_2 can be concluded to have a higher probability of also being disrupted (due to disruption propagation). Furthermore, if there are other nodes pointing to n_1, those nodes are also likely to be disrupted. Therefore, after each scan, the disruption probability map should be updated accordingly to decide the next best nodes to scan. Inference methods include node degree analysis, adaptive scanning (Dusadeerungsikul & Nof, 2019), and Bayesian network inference (Nguyen et al., 2021).

In the example of strategic prevention (Nguyen, 2020), strategic resources can be deployed to prevent disruptions, but no dynamic response capability exists. Disruptions are also not known to the operator ahead of time. The strategic resources can also cover multiple nearby nodes. This example tests the extent of damages that the affected system suffers after a certain amount of time. In this example, effective network analysis was found to provide better disruption prevention results. In this example, both degree centrality and harmonic centrality were applied with prevention coverage analysis to calculate the best allocation combination. Numerical experiments indicated that coverage analysis provided significantly better system resilience.

3.6 Food Supply Chain Security by Agricultural Robotic Systems for Early Detection, Diagnosis, and Treatment

Preventing crop yield losses is one of the major concerns in food supply chain security (Cowling et al., 2019). Agriculture plants can experience various stressors such as changing temperature, disease emergence, and humidity level fluctuation (Bloch et al., 2015). These stressors can cause plants to develop diseases that eventually damage crop yields (Ari et al., 2015). To avoid loss in agricultural supply productivity, the Agricultural Robotics System (ARS) has been developed and employed to detect stress early, diagnose the current status of the plant, and provide timely treatments (Guo et al., 2018; Nair et al., 2021). In this section, the ARS framework is discussed, and its case studies are presented.

3.6.1 ARS Framework

The main task of ARS is to scan plants, identify plants' status, and request the treatment robot (if necessary) (Dusadeerungsikul et al., 2018). The ARS is developed as a cyber-physical system by connecting three agent types (i.e., operating agent, data collecting agent, and intelligent agent) and algorithm with Task Administration Protocol (Dusadeerungsikul et al., 2020). In every operation run, the operating agent (such as an agricultural robot) moves into a field to support the data collecting agent (i.e., sensors and cameras) collecting necessary information (Dusadeerungsikul et al., 2019; Nair et al., 2019). The data collected will be analyzed by an intelligent agent (i.e., human agent or expert system) to diagnose the current status of crops utilizing algorithm, e.g., Wang et al., 2018. If the crop has a sign of stress or disease, a treatment robot will be launched, making treatment to minimize yield loss (Nair et al., 2021). In addition, the intelligent agent will be a decision-maker, solving unexpected real-time problems (Dusadeerungsikul, 2020; Sreeram & Nof, 2021). Effective communication and connection of the ARS is provided by an agricultural CPS (Fig. 3.11), which connects the physical agents with the cyber connection.

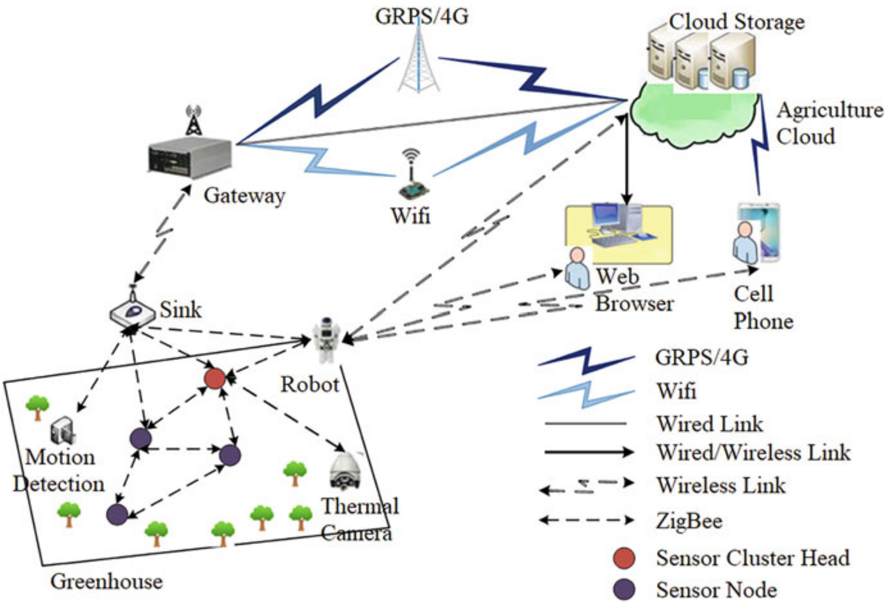


Fig. 3.11 Agricultural CPS network (from Guo et al., 2018)

3.6.2 ARS Case Studies

The ARS framework has been applied to various applications and contexts to test and validate the efficiency of the designed system under dynamically changing conditions and situations. In addition, task administration (collaboration) protocols have been developed to support the operation in ARS. The followings are three examples of case studies.

3.6.2.1 Case 1: Communication and Connection in ARS (Guo et al., 2018)

The first case is developed to test the communication and connection efficiency in ARS. Two systems, namely ARS with agricultural CPS and ARS with non-CPS, are implemented and compared. (Note that the designed CPS for ARS is called Monitoring, detecting, and responding-CPS or MDR-CPS.) The experiments have been conducted in two situations; a normal situation and a situation with conflicts and errors. Results are summarized as follows.

1. ARS operates in a normal situation.

In this case, the systems are assigned with locations to scan plants. Then, the total time to complete all assignments or total operation time is captured as a metric comparing two systems. The results show that MDR-CPS has outperformed the alternative design (without real-time cyber-based decisions and control) by yielding significantly lower total operation time. Therefore, MDR-CPS, which allows more effective communication, analysis, and connection among agents, delivers better performance than the alternative with the same resources.

2. ARS operates in a situation where conflicts and errors emerge.

The second situation focuses on dynamic disruptions caused by system conflicts and errors.

Conflicts and errors can be defined in Eqs. (3.8) and (3.9) (Nof et al., 2015).

Conflicts:

$$\exists \text{Conflict}\left[\text{ARS}_i\left(t\right)\right]; \text{if State}\left[\text{ARS}_i\left(t\right)\right] \overset{\text{Dissatisfy}}{\rightarrow} \gamma\left(t\right) \tag{3.8}$$

Errors:

$$\exists \text{Error}\left[\text{ARS}_i\left(t\right) \cup \text{ARS}_j\left(t\right)\right]; \text{if State}\left[\text{ARS}_i\left(t\right) \cup \text{ARS}_j\left(t\right)\right] \overset{\text{Dissatisfy}}{\rightarrow} \gamma\left(t\right) \tag{3.9}$$

Where $\text{ARS}_i(t)$ and $\text{ARS}_j(t)$ are ARS's agents at time t, and State[•] is a state of agents. $\gamma(t)$ is set of constraints at time t.

The systems are assigned with the same assignment as in the previous experiment, but there will be conflicts and errors during the operation (which have been

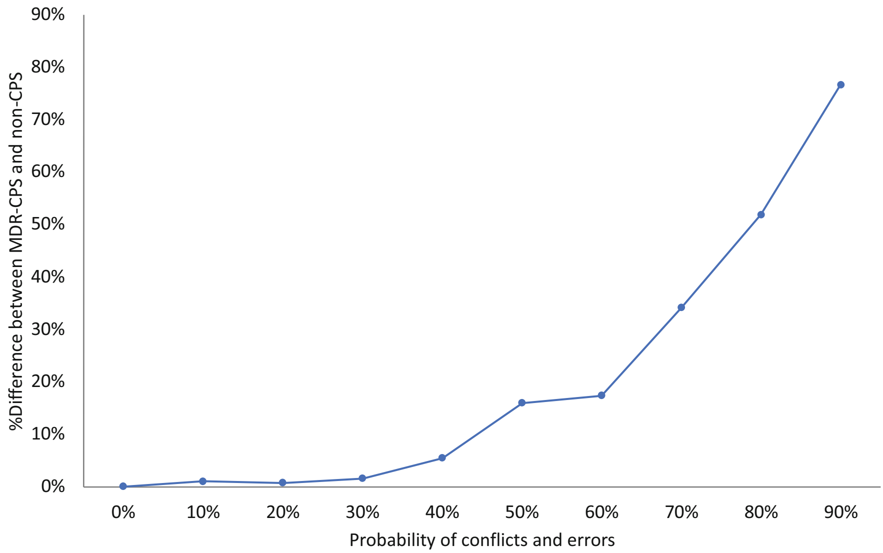


Fig. 3.12 Percentage difference in total operation time between MDR-CPS and non-CPS for each conflict and errors level

ignored in the previous case). The conflicts and errors could be, for example, unidentified plant status or data transmission incomplete. The probability of conflicts and errors varies from 0% (perfect system) to 90% (highly unreliable system). Results show that both systems (MDR-CPS and ARS with non-CPS) require additional time to complete the same tasks. The total operation time of ARS with non-CPS, however, significantly increases than relative to MDR-CPS (Fig. 3.12). It can be concluded that the MDR-CPS helps ARS to stabilize the system, even though some unexpected conflicts and errors emerge.

3.6.2.2 Case 2: Collaboration of ARS's Agents (Dusadeerungsikul & Nof, 2019)

The example of implementing ARS with agricultural CPS and focusing on agents' collaboration and operation efficiency is presented in Dusadeerungsikul and Nof (2019). The Collaborative Control Protocol for Early Detection (CCP-ED) of stress in plants has been designed to support ARS agents' collaboration. CCP-ED aims to synchronize ARS agents to minimize total operation costs. The newly designed protocol is tested and compared with alternatives such as the current practice (which does not apply any collaborative control task administration protocols). The developed protocol shows a significant improvement in system efficiency and ability to indicate the stress location (Fig. 3.13).

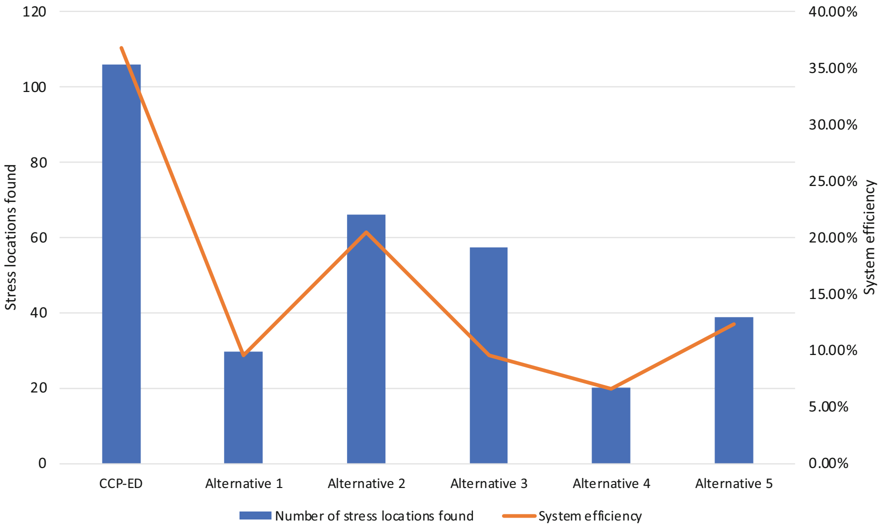


Fig. 3.13 System efficiency and stress location found from CCP-ED and alternative approaches

3.6.2.3 Case 3: Real-Time Information Updating in ARS (Dusadeerungsikul & Nof, 2021)

Lastly, the third case focuses on real-time information updating in ARS. The system with a newly designed protocol called Cyber Collaborative Protocol for Real-Time Communication and Control in ARS (CCP-RTC2) was developed and compared with the current practice (with no cyber collaborative protocol). The experimental results indicate that the CCP-RTC2 is superior to current practice regarding information sharing and information delay (significantly faster information sharing and lower information delay). When the system obtains is subject to an unexpected task request, the CCP-RTC2 can smoothly integrate the request into the work plan and minimize the system's total operation time. Finally, Fig. 3.14 presents the connections of protocols in all case studies to the ARS.

3.7 Cyber Collaborative Control, Optimization, and Harmonization of Smart Warehouse, a Key Element of Supply Network

A warehouse is considered an essential element in the supply chain (Dusadeerungsikul, 2020; Ramaa et al., 2012). It has major impacts on the dynamic behavior of the supply network in which it participates. The operations in the warehouse, such as storing and retrieving packages, directly impact the efficiency

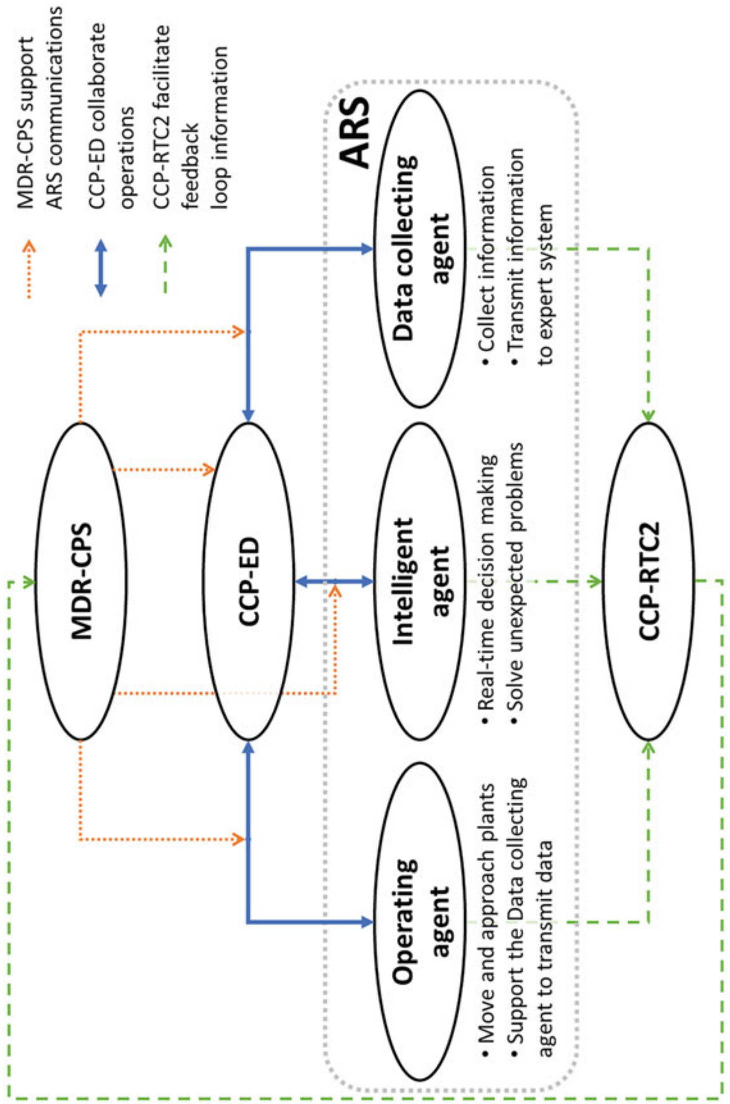


Fig. 3.14 Connections of designed cyber collaborative control protocols supporting ARS network

of the warehouse, hence, the supply chain (Dharmapriya & Kulatunga, 2011). Therefore, an effective and smart warehouse is an important part of improving the supply chain of the future. In this section, the Cyber Collaborative Warehouse (C2W), an effective and smart warehouse, is described and presented.

3.7.1 Cyber Collaborative Warehouse (C2W) Design Concept

The C2W is a cyber-augmented warehouse where warehouse agents can communicate and collaborate in real-time (Dusadeerungsikul et al., 2019). Agents in C2W can be categorized into human operators, warehouse robots, and warehouse shelves (Fig. 3.15). Human operators are the decision-makers who will supervise, correct or input missing data (Huang et al., 2020). In addition, when an unexpected problem occurs, the human operators will utilize experience to solve the problem in real-time. According to the assignment, warehouse robots are the main operating agents that store or retrieve packages. Moreover, different warehouse robots have different capabilities. To illustrate, the following example describes a case study of a C2W design. Suppose a warehouse robot 1 (or "agent type 1") operates faster than robot 2 (or "agent type 2") because of the machine's capability. Agent type 1, however, will typically cost more than agent type 2. Also, two robots can collaborate (and called "agent type 3") for better performance, but their team also increases the operation cost. In addition, suppose there are five types of packages in C2W, categorized based on storage requirement procedure. Table 3.2 presents an example of package types in C2W and agents that can perform each type. For instance, package type 1, the simplest type in this C2W, can be executed by either agent type 1, 2, or 3. On the other hand, package type 5 can be executed only by agent type 3 (the collaboration team), because of weight constraints.

To optimize C2W performance, the Collaboration Requirement Planning protocol for HUB-CI, called CRP-H, is developed (Dusadeerungsikul et al., 2021). The CRP-H optimizes the C2W operation in two phases, the Optimizer and the Harmonizer. The Optimizer is responsible for assigning packages to an agent (type 1, 2, or 3), utilizing a mathematical model. Therefore, the Optimizer requires high computational power and long computational time to deliver output. The Optimizer's output is an assignment list indicating which agent is responsible for each package. Then, the Harmonizer will determine the sequence of each package at each agent. In addition, the Harmonizer may receive additional requirements during the operation run. Therefore, the Harmonizer requires flexibility to cope with the uncertainty of the system. Hence, simple rules and heuristics are maintained in the Harmonizer. Figure 3.15 presents the architecture of C2W.

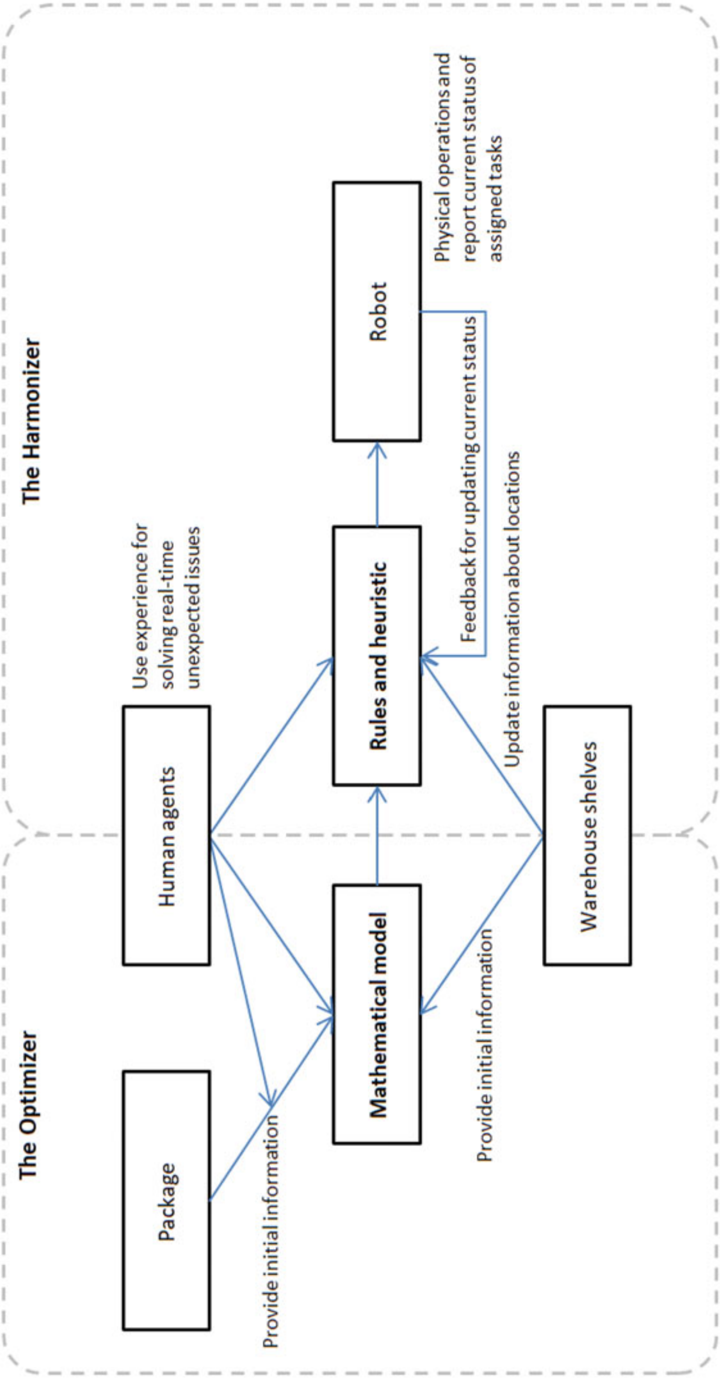


Fig. 3.15 C2W architecture, Cyber Collaborative Warehouse general architecture

Table 3.2 Packages types and agent types in the C2W Case Study

	Agent type 1 (Robot 1)	Agent type 1 (Robot 2)	Agent type 3 (Robot 1 + 2)
Package type 1	✓	✓	✓
Package type 2	✓	–	✓
Package type 3	–	✓	✓
Package type 4	✓	✓	–
Package type 5	–	–	✓

3.7.2 C2W Case Study

An example of applying the C2W concept is presented in Dusadeerungsikul et al. (2021). The C2W is validated against the current practice (operating the C2W without the collaboration task administration protocols). Three performance indicators are utilized in the experiment: total operation cost (Eq. 3.10), makespan (Eq. 3.11), and total weighted completion time (Eq. 3.12).

$$\text{Total operation cost} = \sum_i \cos \text{t}_i \tag{3.10}$$

$$\text{Makespan} = \max_i (\text{completion\_time}_i) \tag{3.11}$$

$$\text{Total weighted completion time} = \sum_i \text{weight}_i \times \text{completion\_time}_i \tag{3.12}$$

Where $\text{cos}t_i$ is cost of storing package i, $\text{completion} \_ \text{time}_i$ is the finished time of storing package i, and weight_i is priority of package i.

Three situations are utilized for the experiments by computer simulation. The results are presented as follows.

1. Performance Analysis in a Normal Situation

The first situation is where all information, such as package information and agent capabilities, are available before the operation begins. In the experiment, 100 packages with different priorities are assigned to the system with two robots. The experimental results show (Fig. 3.16) that CRP-H significantly outperforms today's common practice at a 0.95 statistical confidence level. CRP-H minimizes total operation cost because of the Optimizer, which optimally assigns packages to the robot or robot team. In addition, the Harmonizer minimizes the system's makespan and total weighted completion time by the designed algorithm. Notably, the makespan from the CRP-H has met the guarantee bound in the Theorem proved in Dusadeerungsikul et al. (2021).

2. Performance Analysis in a Situation with Unexpected Task Requests

The second scenario is when the system receives unexpected task requests and needs to integrate the requests into the current task execution plan. This situation

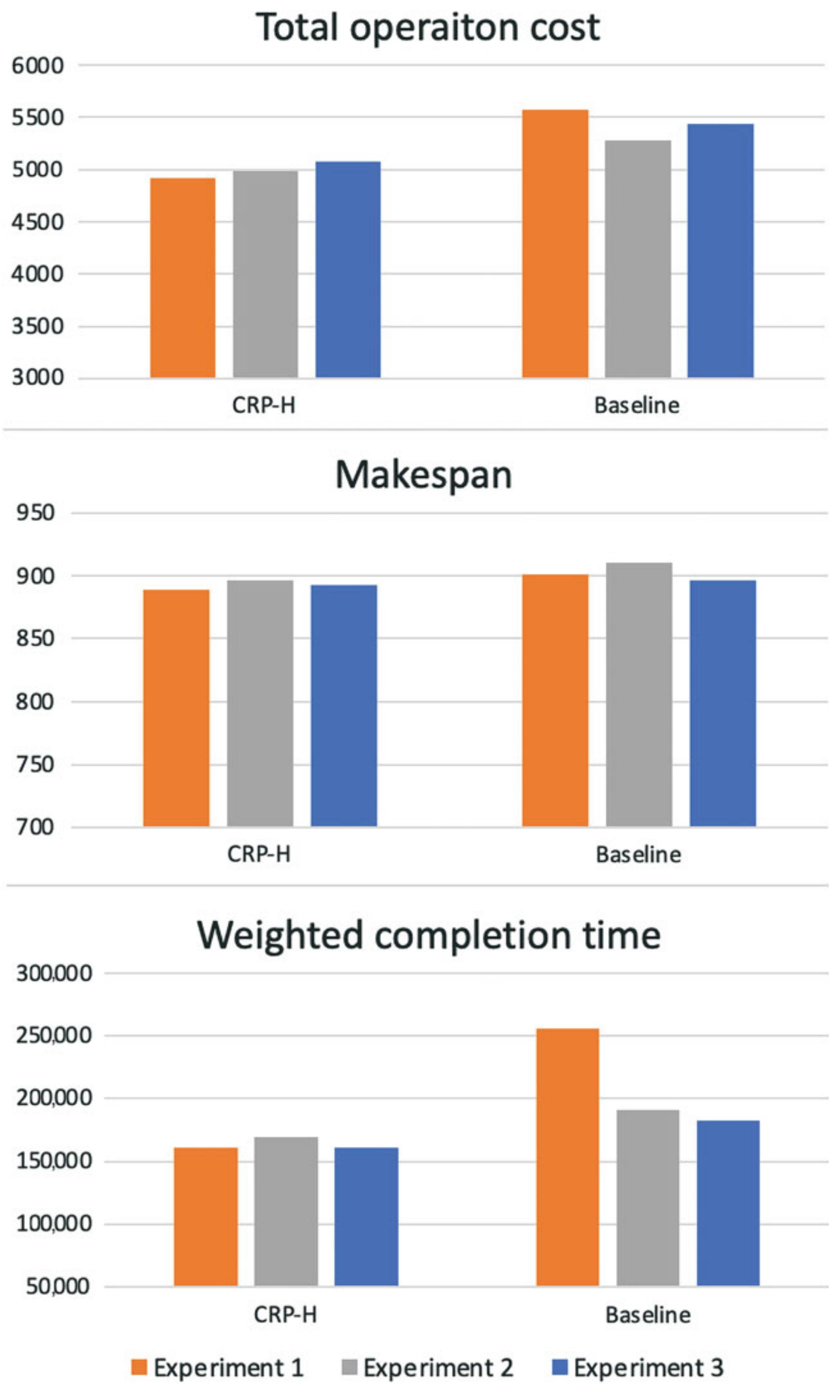


Fig. 3.16 Total operation cost, Makespan, and Weighted completion time from three experiments

can happen in the real world to respond and support the dynamic requirements and order changes of customers. The scenario begins with the system assigned with 90 packages; then, additional ten unexpected task requests randomly arrive to the system for integrating them into the current, ongoing plan. The experimental results (Fig. 3.16) indicate that the CRP-H yields better performance relative to the alternative design of the current practice (without CRP-H). The total operation cost from CRP-H is lower relative to the current practice, as well as the total weighted completion time and makespan.

3. Performance Analysis with Missing Information

The last scenario is when some information, such as package priority, is missing. In CRP-H, the human agent is integrated into the system. The human agent can fill in the missing information base on their prior knowledge and experience. An alternative design commonly used in the current practice is to replace any missing information by default values without asking a human agent. The situation analysis and comparison begin with 100 packages with of them ten missing information about their assigned priorities. The experimental results (Fig. 3.16) show that with human intervention in the package sequencing process, the system's performance improves significantly. The total operation cost for CRP-H is statistically lower than the current practice. In addition, total weighted completion time and makespan of CRP-H are also minimized and lower than the alternative design. Note that in this experiment, the cost of a human agent is assumed to be zero. If there is an additional cost for having a human agent, the additional cost must be considered in the total operation cost of CRP-H.

3.7.3 C2W in the Supply Network

Considering the roles and implications of CRP-H and smart warehouses in the supply network, CRP-H saves both money and time in a smart warehouse, and consequently, in the supply network, without additional investment besides the CCT-based design. In practical cases, where the warehouse operates continuously, practitioners may let the Optimizer and the Harmonizer run in parallel. For example, practitioners can group the tasks according to the arrival time for the Optimizer runs. Then, input the Optimizer's resulting plans to the Harmonizer for physical execution. In addition, the new arrival tasks can be grouped for another Optimizer run during the physical execution of the just previous plans being considered by the Harmonizer. By following the described procedure, the warehouse can operate continuously without interruption or delay.

3.8 Conclusion

The collaborative control principles and protocols relevant to the control of supply chains and supply networks (as defined in Sect. 3.1) are discussed and explained in this chapter.

- Effective collaborative control and collaboration engineering are required in modern supply, especially with increasingly advanced ICT, IoT/IoS, and cyber intelligence.
- This requirement is further emphasized by the multiple parties involved in the many supply processes, activities, and interactions, all subjected to errors; conflicts; small, large, and massive disruptions; and dynamic changes.
- Using the approaches and tools explained in this chapter, supply managers, engineers, and executives can employ the collaborative control engineering principles to their relevant supply systems and processes: further improving their:
  - Resilience
  - Service quality
  - Effectiveness
  - Predictive deliveries, and
  - Efficiency

Ongoing projects and research aim to further refine the theoretical techniques and respond to further challenges facing future supply chains and supply networks.

Acknowledgment The research reported here has been partially supported by the Purdue University PRISM Center for Production, Robotics, and Integration Software for Manufacturing & Management; BARD Grant IS-4886-16R: Development of a Robotic Inspection System for Early Identification and Locating of Biotic and Abiotic Stresses in Greenhouse Crops; and the National Science Foundation Award 1839971 FW-HTF: Collaborative Research: Pre-Skilling Workers, Understanding Labor Force Implications and Designing Future Factory Human-Robot Workflows Using a Physical Simulation Platform. The authors also express deep appreciation to the many PRISM and PGRN colleagues and affiliated supply companies worldwide who participated in the research projects, discoveries, and implementations reported in this chapter.

References

Ari, A. A. A., Gueroui, A., Labraoui, N., & Yenke, B. O. (2015). Concepts and evolution of research in the field of wireless sensor networks. arXiv Prepr. arXiv1502.03561.

Bloch, V., Degani, A., & Bechar, A. (2015). Task characterization and classification for robotic manipulator optimal design in precision agriculture. In *Precision agriculture'15* (pp. 247–257). Wageningen Academic Publishers.

Burgos, D., & Ivanov, D. (2021). Food retail supply chain resilience and the COVID-19 pandemic: A digital twin-based impact analysis and improvement directions. *Transportation Research Part E: Logistics and Transportation Review, 152*, 102412.

Chen, X. W., & Nof, S. Y. (2012a). Conflict and error prevention and detection in complex networks. *Automatica, 48*, 770–778. https://doi.org/10.1016/j.automatica.2012.02.030

Chen, X. W., & Nof, S. Y. (2012b). Constraint-based conflict and error management. *Engineering Optimization, 44*, 821–841. https://doi.org/10.1080/0305215X.2011.613466

Chopra, S., & Sodhi, M. (2014). Reducing the risk of supply chain disruptions. *MIT Sloan Management Review, 55*, 72–80.

Cowling, W. A., Li, L., Siddique, K. H. M., Banks, R. G., & Kinghorn, B. P. (2019). Modeling crop breeding for global food security during climate change. *Food and Energy Security, 8*, e00157.

Dharmapriya, U. S. S., & Kulatunga, A. K. (2011). New strategy for warehouse optimization–lean warehousing. In *Proceedings of the 2011 International Conference on Industrial Engineering and Operations Management* (pp. 513–519).

Dolgui, A., & Ivanov, D. (2020). Exploring supply chain structural dynamics: New disruptive technologies and disruption risks. *International Journal of Production Economics, 229*, 107886.

Dolgui, A., & Ivanov, D. (2021). Ripple effect and supply chain disruption management: New trends and research directions. *International Journal of Production Research, 59*(1), 102–109.

Dusadeerungsikul, P. O. (2020). *Operations analytics and optimization for unstructured systems: Cyber collaborative algorithms and protocols for agricultural systems*. PhD Dissertation, Purdue University School of Industrial Engineering, West Lafayette, IN. https://doi.org/10.25394/PGS.12218531.v1

Dusadeerungsikul, P. O., He, X., Sreeram, M., & Nof, S. Y. (2021). Multi-agent system optimisation in factories of the future: Cyber collaborative warehouse study. *International Journal of Production Research*, 1–15.

Dusadeerungsikul, P. O., Liakos, V., Morari, F., Nof, S. Y., & Bechar, A. (2020). Smart action. In *Agricultural internet of things and decision support for precision smart farming* (pp. 225–277). Elsevier.

Dusadeerungsikul, P. O., & Nof, S. Y. (2019). A collaborative control protocol for agricultural robot routing with online adaptation. *Computers and Industrial Engineering, 135*, 456–466. https://doi.org/10.1016/j.cie.2019.06.037

Dusadeerungsikul, P. O., & Nof, S. Y. (2021). A cyber collaborative protocol for real-time communication and control in human-robot-sensor work. *International Journal of Computers Communications & Control, 16*.

Dusadeerungsikul, P. O., Nof, S. Y., & Bechar, A. (2018). Detecting stresses in crops early by collaborative robot-sensors-human system automation. In *IISE Annual Conference and Expo 2018* (pp. 1084–1089). Institute of Industrial and Systems Engineers, IISE.

Dusadeerungsikul, P. O., Nof, S. Y., Bechar, A., & Tao, Y. (2019). Collaborative control protocol for agricultural cyber-physical system. *Procedia Manufacturing, 39*, 235–242. https://doi.org/10.1016/j.promfg.2020.01.330

Dusadeerungsikul, P. O., Sreeram, M., He, X., Nair, A., Ramani, K., Quinn, A. J., & Nof, S. Y. (2019). Collaboration requirement planning protocol for hub-Ci in factories of the future. *Procedia Manufacturing, 39*, 218–225. https://doi.org/10.1016/j.promfg.2020.01.327

Floyd, R. W. (1962). Algorithm 97: Shortest path. *Communications of the ACM, 5*, 345. https://doi.org/10.1145/367766.368168

Freeman, L. C. (1978). Centrality in social networks conceptual clarification. *Social Networks, 1*, 215–239. https://doi.org/10.1016/0378-8733(78)90021-7

Ghadge, A., Er, M., Ivanov, D., & Chaudhuri, A. (2021). Visualisation of ripple effect in supply chains under long-term, simultaneous disruptions: A system dynamics approach. *International Journal of Production Research*, 1–14.

Guo, P., Dusadeerungsikul, P. O., & Nof, S. Y. (2018). Agricultural cyber physical system collaboration for greenhouse stress management. *Computers and Electronics in Agriculture, 150*, 439–454. https://doi.org/10.1016/j.compag.2018.05.022

Hosseini, S., & Ivanov, D. (2020). Bayesian networks for supply chain risk, resilience and ripple effect analysis: A literature review. *Expert Systems with Applications, 161*, 113649.

Hosseini, S., & Ivanov, D. (2021). A multi-layer Bayesian network method for supply chain disruption modelling in the wake of the COVID-19 pandemic. *International Journal of Production Research*, 1–19.

Hosseini, S., Ivanov, D., & Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transportation Research Part E: Logistics and Transportation Review, 125*, 285–307. https://doi.org/10.1016/j.tre.2019.03.001

Hosseini, S., Ivanov, D., & Dolgui, A. (2020). Ripple effect modelling of supplier disruption: Integrated Markov chain and dynamic Bayesian network approach. *International Journal of Production Research, 58*, 3284–3303.

Huang, G., Rao, P. S., Wu, M.-H., Qian, X., Nof, S. Y., Ramani, K., & Quinn, A. J. (2020). Vipo: Spatial-visual programming with functions for robot-IoT workflows. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–13).

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

Ko, H. S., & Nof, S. Y. (2010). Design of protocols for task administration in collaborative production systems. *International Journal of Computers Communications & Control, 5*(1), 91–105.

Ko, H. S., & Nof, S. Y. (2012). Design and application of task administration protocols for collaborative production and service systems. *International Journal of Production Economics, 135*, 177–189.

Liu, Y., & Nof, S. Y. (2004). Distributed microflow sensor arrays and networks: Design of architectures and communication protocols. *International Journal of Production Research, 42*, 3101–3115. https://doi.org/10.1080/00207540410001699363

Moghaddam, M., & Nof, S. Y. (2014). Combined demand and capacity sharing with best matching decisions in enterprise collaboration. *International Journal of Production Economics, 148*, 93–109. https://doi.org/10.1016/j.ijpe.2013.11.015

Moghaddam, M., & Nof, S. Y. (2016a). Real-time optimization and control mechanisms for collaborative demand and capacity sharing. *International Journal of Production Economics, 171*, 495–506.

Moghaddam, M., & Nof, S. Y. (2016b). *Best matching theory & applications.*

Nair, A. S., Bechar, A., Tao, Y., & Nof, S. Y. (2019). The HUB-CI model for telerobotics in greenhouse monitoring. *Procedia Manufacturing, 39*, 414–421.

Nair, A. S., Nof, S. Y., & Bechar, A. (2021). Emerging directions of precision agriculture and agricultural robotics. In *Innovation in agricultural robotics for precision agriculture* (pp. 177–210). Springer.

Nguyen, W. P. V. (2020). *Collaborative response to disruption propagation (CRDP)*. PhD Dissertation, Purdue University School of Industrial Engineering, West Lafayette, IN.

Nguyen, W. P. V., Dusadeerungsikul, P. O., & Nof, S. Y. (2021). Plant stress propagation detection and monitoring with disruption propagation network modelling and Bayesian network inference. *International Journal of Production Research*, 1–19. https://doi.org/10.1080/00207543.2021.2009139

Nguyen, W. P. V., Nair, A. S., & Nof, S. Y. (2019). Advancing cyber-physical systems resilience: The effects of evolving disruptions. In *ICPR-25*. Procedia Manufacturing.

Nguyen, W. P. V., & Nof, S. Y. (2018). Resilience informatics for cyber-augmented manufacturing networks (CMN): Centrality, flow and disruption. *Studies in Informatics and Control, 27*, 377–384. https://doi.org/10.24846/v27i4y201801

Nguyen, W. P. V., & Nof, S. Y. (2019). Collaborative response to disruption propagation (CRDP) in cyber-physical systems and complex networks. *Decision Support Systems, 117*, 1–13. https://doi.org/10.1016/j.dss.2018.11.005

Nguyen, W. P. V., & Nof, S. Y. (2020). Strategic lines of collaboration in response to disruption propagation (CRDP) through cyber-physical systems. *International Journal of Production Economics, 230*, 107865.

Nof, S. Y. (2007). Collaborative control theory for e-Work, e-Production, and e-Service. *Annual Reviews in Control, 31*, 281–292. https://doi.org/10.1016/j.arcontrol.2007.08.002

Nof, S. Y., Ceroni, J. A., Jeong, W., & Moghaddam, M. (2015). *Revolutionizing collaboration through e-work, e-business, and e-service*. Springer ACES Series.

Panetto, H., Iung, B., Ivanov, D., Weichhart, G., & Wang, X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control, 47*, 200–213.

Ramaa, A., Subramanya, K. N., & Rangaswamy, T. M. (2012). Impact of warehouse management system in a supply chain. *International Journal of Computers and Applications, 54*.

Reyes Levalle, R. (2015). *Resilience by teaming in supply chains and supply networks*. Springer ACES Series.

Reyes Levalle, R. (2018). *Resilience by teaming in supply chains and networks*. Springer ACES Series.

Reyes Levalle, R., & Nof, S. Y. (2015a). Resilience by teaming in supply network formation and re-configuration. *International Journal of Production Economics, 160*, 80–93.

Reyes Levalle, R., & Nof, S. Y. (2015b). A resilience by teaming framework for collaborative supply networks. *Computers and Industrial Engineering, 90*, 67–85.

Reyes Levalle, R., & Nof, S. Y. (2017). Resilience in supply networks: Definition, dimensions, and levels. *Annual Reviews in Control, 43*, 224–236. https://doi.org/10.1016/j.arcontro1.2017.02.003

Scavarda, M., Seok, H., & Nof, S. Y. (2017). The constrained-collaboration algorithm for intelligent resource distribution in supply networks. *Computers and Industrial Engineering, 113*, 803–818. https://doi.org/10.1016/j.cie.2017.05.015

Seok, H., Kim, K., & Nof, S. Y. (2016). Intelligent contingent multi-sourcing model for resilient supply networks. *Expert Systems with Applications, 51*, 107–119.

Seok, H., & Nof, S. Y. (2013). Dynamic coalition reformation for adaptive demand and capacity sharing. *IIE Annual Conference and Expo 2013, 147*, 106–113.

Seok, H., & Nof, S. Y. (2014). Collaborative capacity sharing among manufacturers on the same supply network horizontal layer for sustainable and balanced returns. *International Journal of Production Research, 52*, 1622–1643.

Seok, H., & Nof, S. Y. (2018). Intelligent information sharing among manufacturers in supply networks: Supplier selection case. *Journal of Intelligent Manufacturing, 29*, 1097–1113. https://doi.org/10.1007/s10845-015-1159-9

Sreeram, M., & Nof, S. Y. (2021). Human-in-the-loop: Role in cyber physical agricultural systems. *International Journal of Computers Communications & Control, 16*.

Tkach, I., & Edan, Y. (2020). *Distributed heterogeneous multi sensor task allocation systems*. Springer ACES Series.

Tkach, I., Edan, Y., & Nof, S. Y. (2017). Multi-sensor task allocation framework for supply networks security using task administration protocols. *International Journal of Production Research, 55*, 5202–5224.

Wang, D., Vinson, R., Holmes, M., Seibel, G., Bechar, A., Nof, S. Y., Luo, Y., & Tao, Y. (2018). *Early tomato spotted wilt virus detection using hyperspectral imaging technique and outlier removal auxiliary classifier generative adversarial nets (OR-AC-GAN)*. http://elibrary.asabe.org/abstract.asp?aid=49283&t=5

Yoon, S. W., Matsui, M., Yamada, T., & Nof, S. Y. (2011). Analysis of effectiveness and benefits of collaboration modes with information- and knowledge-sharing. *Journal of Intelligent Manufacturing, 22*, 101–112.

Yoon, S. W., & Nof, S. Y. (2010). Demand and capacity sharing decisions and protocols in a collaborative network of enterprises. *Decision Support Systems, 49*, 442–450. https://doi.org/10.1016/j.dss.2010.05.005

Yoon, S. W., & Nof, S. Y. (2011). Affiliation/dissociation decision models in demand and capacity sharing collaborative network. *International Journal of Production Economics, 130*, 135–143.

Zhong, H. (2016). *Dynamic lines of collaboration in e-Work systems*. ProQuest Dissertations & Theses.

Zhong, H., & Nof, S. Y. (2015). The dynamic lines of collaboration model: Collaborative disruption response in cyber–physical systems. *Computers and Industrial Engineering, 87*, 370–382. https://doi.org/10.1016/j.cie.2015.05.019

Zhong, H., & Nof, S. Y. (2020). *Dynamic lines of collaboration: Disruption handling & control*. Springer Springer ACES Series.

Zhong, H., Nof, S. Y., & Filip, F. G. (2014). Dynamic lines of collaboration in CPS disruption response. *IFAC Proceedings, 47*, 7855–7860. https://doi.org/10.3182/20140824-6-ZA-1003.02403

Chapter 4
Managing Supply Chain Disruption by Collaborative Resource Sharing

Melanie Kessler and Julia C. Arlinghaus

Abstract The highly interconnected and global supply chains have faced tremendous challenges since 2019. Global conflicts, natural disasters, wars, and the COVID-19 pandemic repeatedly cause supply chain disruptions and pose major challenges for the globalized supply networks in regard to robustness and resilience. The increasing interconnectivity makes supply chains more vulnerable to disruption and it seems that the proverbial stone that falls into the water actually causes a flood at the other end of the supply chain. This enhances the requirement for an effective risk management. Based on a survey of 216 supply chain risk managers of European production firms, this study introduces the collaborative sharing of production and human resources as a method to recover from disruptions. Thereby, trust and commitment are identified as the core values for collaborative resource sharing to increase supply chain resilience. We propose a framework to explicate the main drivers for collaborative human resource and production sharing and give first practical recommendations for supply chain risk managers to support the process of the development of mitigation strategies to recover from supply chain disruptions.

Keywords Collaborative resource sharing · Supply chain risk management · Rational view theory · Supply chain resilience · Intertwined supply network

4.1 Introduction

The increasing frequency of risks, higher uncertainty, and disruptions is one major challenge for supply chain management (Ivanov & Dolgui, 2020). Due to the increasing connection between supply chain partners and the increasing complexity

M. Kessler (✉)
RWTH Aachen University, Aachen, Germany
e-mail: melanie.kessler@rwth-aachen.de

J. C. Arlinghaus
Otto von Guericke University, Magdeburg, Germany
e-mail: julia.arlinghaus@ovgu.de

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_4

even small disturbances lead to sensitive interruptions. Due to delivery shortages for electronic components from Ukraine production locations several car manufactures and automotive suppliers had to shut down their assembly lines in Germany and had to register short-time work (Piller, 2022). Apple had to shut down some production sites as their top manufacturer Foxconn in Shenzhen had to close its factory due to the resurgent COVID-19 wave for which the Chinese government had introduced another complete lockdown for some cities (Fortune, 2022). These are just two events of a wide and constantly increasing range of disruptive supply chain events.

A report of EventWatch from 2018 confirms a significant increase in disruption events whether from natural catastrophes (earthquakes, flood, etc.), legal changes (regulations, sanctions), or political events (war, strike) (Burson, 2019). Therefore, current supply chain risk management (SCRM) faces tremendous challenges to cope with these risks and define adequate mitigation strategies to increase supply chain resilience (Christopher & Holweg, 2017). Especially the supply of energy and coping with the scarce resources is one of the major challenges for today's supply chains. As supply chains are highly connected with a high degree of interfirm relationships also a collaborative risk management approach is required to mitigate these disruptions (Friday et al., 2018; Ivanov, 2021). However, current SCRM approaches still focus on individual firm strategies and lack an overarching view (Munir et al., 2020). Therefore, Li et al. (2015) emphasize the need for a collaboratively end-to-end approach in SCRM. Subsequently, Pettit et al. (2013) have identified collaborative approaches for disruption management as a key success factor for supply chain resilience. Nevertheless, current literature lacks how collaboration relates to supply chain resilience and what factors must be considered to establish a successful collaborative resource sharing (Duong & Chong, 2020).

We aim to contribute to this research gap by answering the research question: "How does collaborative resource sharing enable supply chain disruption management?" The remainder of this chapter is structured as follows. Section 4.2 gives an overview of the status in literature regarding the concept of collaborative resource sharing and its influence on supply chain resilience and robustness. We further introduced the concept of the rational view theory, trust, and commitment as a key enabler for collaborative resource sharing. Section 4.3 shows the applied research methodology regarding the survey and further expert interviews. Section 4.4 presents the findings and is followed by a discussion and conclusion in Sect. 4.5.

4.2 Theoretical Background

4.2.1 Supply Chain Resilience and Robustness

As supply chain risks cannot be prevented completely it is also important to react quickly and cost-effectively to disruptions (Melnyk et al., 2010).

Therefore, resilience and robustness are one of the key requirements for supply chain risk management nowadays (Ivanov, 2018). Thereby, supply chain resilience can be defined as the “ability of a system to return to its original state, within an acceptable period of time, after being disturbed” (Christopher & Peck, 2004). Whereas resilience focuses more on reestablishing the baseline situation, robustness as defined by Kitano (2004) is the “ability of the supply chain to maintain its function despite internal or external disruptions.” A robust supply chain is able to withstand risks and maintain its operation (Brandon-Jones et al., 2014).

Thereby, creating resilience and robustness cannot be seen as a one-time event after a disturbance, rather it requires a continuously process (Pettit et al., 2013).

Especially, with the number of increasing disruption events maintaining resilience and robustness becomes more and more important while at the same time also more difficult to achieve. The increasing interlinkages between supply chain partners, reduced inventory levels, logistic concepts such as just in time and just in sequence delivery makes supply chains prone to disruptions with the requirement of a joint answer (Brandon-Jones et al., 2014). Nevertheless, companies still focus on company individual preventive approaches (Marchese & Paramasivam, 2013). However, a collaborative approach based on resource and information sharing among supply chain partners reduce uncertainty and risks significantly (Ivanov 2020).

4.2.2 Collaborative Resource Sharing

A collaborative approach enables the development of synergies among supply chain partners (Whipple & Russell, 2007). This grants the possibility to achieve a higher benefit than the companies would have achieved individually (Cao et al., 2010). Literature provides various examples which confirm the positive impact of supply chain collaboration on performance (Chen et al., 2004). As disruptive events occur network wide the response can also just be from the whole network as well (Christopher & Peck, 2004).

Information exchange, joint planning, and the development of plans to synchronize operations are the basic instruments for collaborative activities (Nyaga et al., 2010). Cao et al. (2010) developed a well-elaborated conceptualization of supply chain collaboration. They define (1) information sharing, (2) goal congruence, (3) decision synchronization, (4) incentive alignment, (5) resource-sharing, (6) collaborative communication, and (7) joint knowledge creation as the basic principles for an effective joint approach to react on disruptions. Thereby, the selection of the best fitting set of resources should be combined by the supply chain partners to create competitive advantages (Bovell, 2012). Ambulkar et al. (2015) define the ability to reconfigure resources as a crucial success factor to achieve supply chain resilience and see collaborative resource sharing as an effective proactive as well as reactive risk management method. Especially trust and commitment are the prerequisite for this and lead to a positive impact (Bode et al., 2011).

The research of Wieland and Wallenburg (2013) confirms the positive correlation of communication and commitment for a collaborative risk management approach. Within the limited range of literature regarding collaborative resource sharing Cao and Zang (2013) emphasized the lack of studies on collaborative resource sharing in supply chain management. A detailed analysis of the necessary capabilities that enables a collaborative resource sharing remains at a silent place in literature (Friday et al., 2018).

In the cross-sectoral context, Ivanov and Dolgui (2020) and Ivanov (2021) introduced the concept of intertwined supply networks. The key idea of this concept is to utilize the synergetic effects of intersections between supply chains of different industrial sectors (e.g., automotive and healthcare) and to make use of resource-sharing effects.

4.2.3 Relational View Theory

Among the theories used in collaborative resource-sharing literature the most appropriate is the relational view theory showing the significance of relational dimensions (Carey et al., 2011; Brüning & Bendul, 2017). Dyer and Singh (1998) were one of the first who introduced the concept of the relational view theory with a more overarching view instead of a company individual focus. Based on the concept of interlinked networks they state that these inter-firm linkages and interorganizational resources may be a source of relational rents and collaborative performance increase across the entire network. They analyzed four key resources which contribute to relational rents and joint value creation: (1) investment in relational-specific assets, (2) substantial knowledge exchange, (3) combining of complementary, but scarce resources or capabilities, and (4) lower transaction costs than competitor alliances. The available resources within the network represent the complementary resource endowments (Dyer & Singh, 1998). Thereby, companies are able to obtain value from resources that are not fully controlled by their own (Lavie, 2006).

4.2.4 Trust and Commitment

Trust has been researched intensely in the field of supply chain management (Paluri & Mishal, 2020). Thereby, reliability, predictability, and fairness are the three main characteristics of trust (Agarwal & Shankar, 2003). Moorman et al. (1993), define trust as "the willingness to rely on an exchange partner on whom one has confidence, without worrying about the exposure of one's weakness of vulnerability, and considering the partner as credible, reliable and benevolent, thereby willing to rely on the partner." Trust implies two involved parties the trustor who is in an uncertain situation and the trustee on whom the trust is placed (Mohammed et al., 2010). Thereby especially uncertainty places a crucial role in the definition of trust. Several researchers confirm the positive impact of trust on supply chain performance (McEvily et al., 2003; Ha et al., 2011).

Although trust and commitment is often used synonymously in practice, researchers have developed various methods to measure it and discuss this in literature separately and define commitment as a result of trust in the supply chain (Paluri & Mishal, 2020). Thereby the involved parties are willing to invest in the partnership and share risks to positively influence supply chain performance (Chen et al., 2011).

4.3 Methodology

In order to answer the research question, an online self-administrated survey was chosen as a data collection method. This method allows for statistical generalization and conclusions are projectable to a larger population (Wieland & Wallenburg, 2012).

The online survey was conducted anonymously during February and March of 2016. The survey was sent to 7861 contacts in supply chain management. To enhance the response rate two reminders were sent out, resulting in a final set of 321 participants which means a response rate of 5.4%. One hundred and five responses had to be excluded due to large incomplete answers, leaving a usable data set of 216 responses.

The questionnaire consists of 48 questions categorized into four sections. Table 4.1 gives an overview of the structure of the questionnaire.

In the introduction section, the research topic and aim of the survey was presented to the participants. Further, some terms such as "time to recover" or "severity" were explained to the participants.

Section A consisted of questions to identify the current status of SCRM in the companies. Participants were asked about their risk management methods, relevance of SC disruptions, and organization of recoveries.

Sections B and C contained the questions relevant to collaborative resource sharing and recovery before and during a supply chain disruption. Therefore, participants were asked to base their answers on a specific SC disruption that they had experienced in the 5 years preceding the data collection. Respondents that had not experienced SC disruptions were questioned about their hypothetical expectations and willingness with regard to collaborative recovery.

The final section D included classification questions regarding industry, company size, etc.

In order to ensure a structured data analysis, the questions were closed questions with predetermined respond categories.

The questionnaire was distributed in a German and English versions. To ensure comprehensibility the questionnaire was tested beforehand with 11 people from academia and industry and their feedback was included in the final survey design.

Table 4.1 Survey design

Section in the survey questionnaire	Contribution to research
Introduction	
Section A: Recovering from supply chain disruptions: 7 questions	Current status of supply chain risk management
Section B: Collaboration during the supply chain disruption: 19 questions	Framework development
Section C: Relationship characteristics before the disruption: 14 questions	Framework development
Section D: General information about you and your company: 8 questions	Framework development

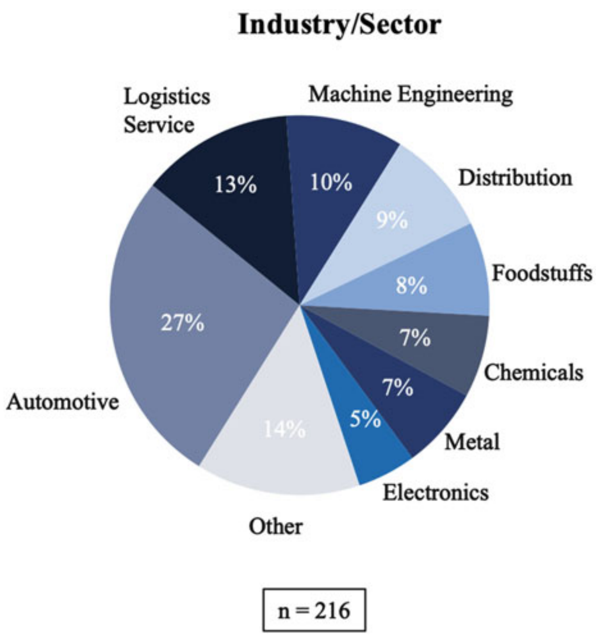


Fig. 4.1 Industry sector of surveyed companies

As Figure 4.1 shows, the majority of the participants are located in the German-speaking area (Germany 76%, Switzerland: 11%, Austria: 3%). International participants were located in France (1%) and the USA (4%). The industries correspond with the most important branches in the German industry landscape (Fig. 4.1).

Also, the company sizes reflect the industrial landscape of the German-speaking area with the majority of small- and medium-sized enterprises (Fig. 4.2).

To test for non-response bias, Chi-square tests were applied to compare early to late respondents' answers in terms of participant's experience in company and company size (annual sales and number of employees) (Wagner & Kemmerling,

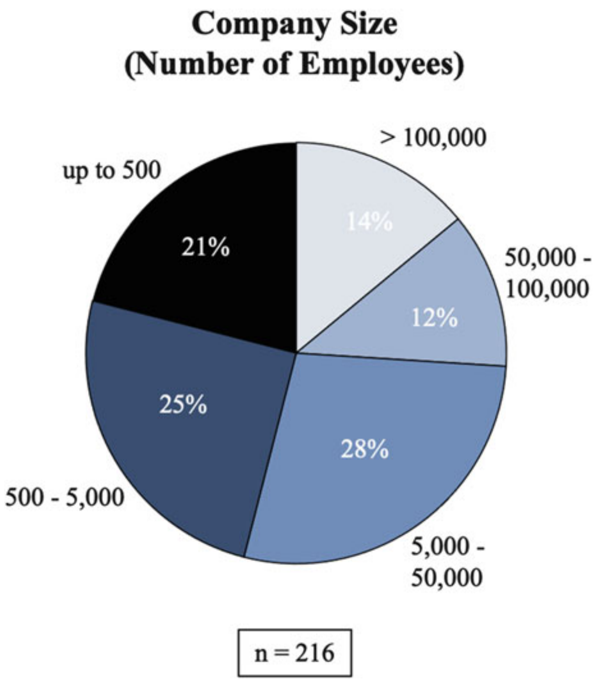


Fig. 4.2 Company size of surveyed companies

2010). Based on the result of 0.25 between the two groups across all three analyzed categories the absence of non-response biases is assumed. Further to keep the influence of the common method bias low several measures were considered in the survey design (Guide & Ketokivi, 2015). Thus, confidentially and anonymity of the respondents' answers was explained in the introduction section to reduce socially desirable responses. The structure of the asked questions was split up into different categories and formulated in a simple and concise way and specific terms were explained. Furthermore, different measurement scales were used.

In addition, eight expert interviews with companies from automotive, aerospace, insurance, and consulting were conducted to discuss the impressions from the survey. The interviews were held in person or via telephone and took between 60 and 90 min and followed a semi-structured approach.

4.4 Findings

The survey showed that 99% of the asked companies already faced a disruption, which confirms that supply chain disruptions cannot be completely eliminated by supply chain risk management. Further, 56.7% stated that this poses a major challenge for their company and still 32.1% rated this a moderate problem. The search and definition of adequate recovery methods is therefore one major challenge for current supply chain risk management. Collaboration is defined as a suitable method to recover from disruptions.

However, our survey showed that the full potential of collaborative resource sharing is still not fully used by the companies.

The major form of collaboration is company internal with subsidiaries or external with different companies such as suppliers, companies from same region or branch or even competitors.

Collaboration within the own company networks requires especially national and international working collaboration. Fifty-three percent of the participants indicated that they already applied internal collaboration as a risk management activity over the past 5 years.

Another form of collaborative recovery is collaboration with other supply chain members. As this requires a close coordination between suppliers, customers, and even sometimes competitors it is less frequently used than internal collaboration. Thirty-five percent of the surveyed companies explained that they used this method as a supply chain risk management activity. Asked with which partner the surveyed companies collaborated most. Eighty-one percent of the companies responded with their first-tier supplier. Almost the same amount of 80% stated that they collaborated with their internal company subsidiaries.

The intensity of collaboration decreases downstream the supply chain. So, 51% responded that they applied a collaboration with their second-tier supplier and 33% with their second-tier customers. Especially with competitors only 25% replied that they had never used a collaborative recovery method. As the underlying reason, they named antitrust.

The intensity of the collaboration shows a similar picture. Based on a scale from 1 (low level) to 7 (high level), the intensity of the collaboration was asked. Thereby the intraorganizational collaboration (5.68) and the collaboration with first-tier suppliers (4.99) were the most intensive forms. Also, collaboration with logistics service providers (4.81) was rated relatively high. They were especially described as a neutral partner in crisis and therefore a favored partner in collaboration activities.

Further companies were asked whether they already shared resources as a method to recover from supply chain disruptions. Thereby production and human resources were investigated separately. Human resources particularly define the sharing of employees whereas production resources comprise machines, warehouse capacities, and factory sharing. Based on a scale of 1 "has never" and 7 "has happened very often," the survey showed that especially human resources were shared frequently (4.64). Especially due to the high flexibility and mobility of employees they can easily form cross-company teams. Whereas the transferability of production resources is per definition reality low. Table 4.2 shows the rating of the surveyed companies regarding their experiences with human resource and production resource sharing.

Especially trust and commitment were named by the survey participants as one key factor for a successful collaboration which confirms the relational view theory. This is especially the result of a long term oriented trustworthy relationship beforehand. The intensity of collaboration before the disruption significantly influences the

Table 4.2 Survey results of human resources and production resources sharing (Bendul & Brüning, 2017)

	Scale rate
Human resources	
In our supply network, employees were able to adapt to new tasks	4.64
In our supply network, employees were mobile enough to exchange know-how/expertise	4.59
The members of our supply network used cross-organizational teams	4.49
The members of our supply network shared know-how/expertise	4.44
Our supply network quickly reorganized supply network human resources (employees)	4.01
Production resources	
Our supply network quickly reorganized supply network production resources	3.89
In our supply network, it was possible to adapt production resources to new tasks	3.57
The members of our supply network shared production resources	3.00
In our supply network, production resources were mobile enough to be shared by the members	2.73

level of success and the willingness to also collaborate during a disruption between the supply chain partners. Nevertheless, also the level of dependency influences the willingness to collaborate. Exemplarily, the following example demonstrates this connection. After a fire in a plant in a production site of Philips in Mexico, Nokia as a customer supported during this disruption as they were highly dependent on specific components for the cellphone chip production which they purchased from Philips (Sheffi, 2005).

A close relationship between the supply chain partners becomes especially essential when organizing the collaborative resource sharing. Namely, the survey showed that the majority did not plan the collaboration intensively. Rather fast and flexible commitment was required to collaborate during a disruption. Only 7% agreed upon procedures and defined measures regarding the collaboration form and intensity beforehand. This shows the tremendous potential to integrate collaborative resource sharing as a suitable risk management method and to integrate this in the companies' risk management activities which are intensively defined, discussed, and regularly updated.

Also, regarding the responsibility of the coordination of the collaboration, there is still potential. Forty-seven percent of the participants stated that only one actor was responsible for the organization of the resource sharing. Asked who was responsible for the organization, 93% of the participants answered that their own company had the main responsibility.

Our survey contains several important findings which we summarize in the following model.

Friday et al. (2018) defined a model of six categories of a higher-order concept which are key factors for successful collaborative risk management. Based on our

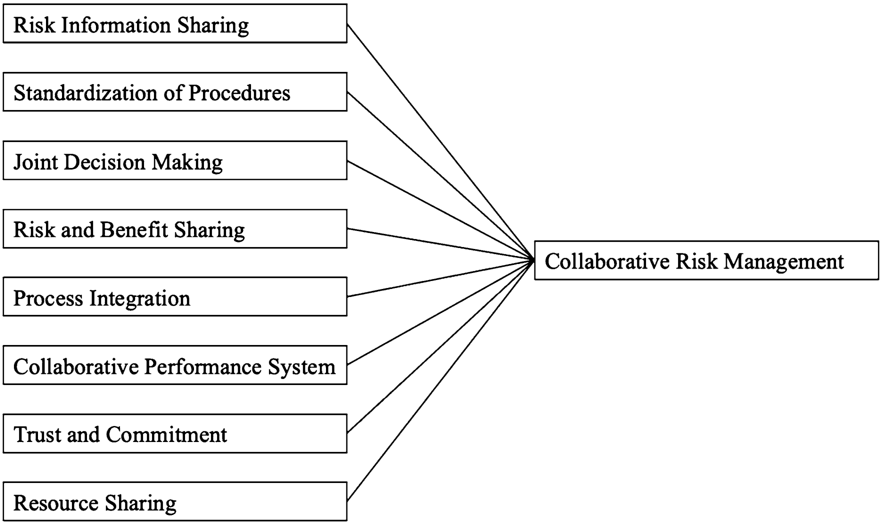


Fig. 4.3 Elaborated concept according to Friday et al. (2018)

findings in the survey we elaborated this concept by adding the categories of trust and commitment as well as resource sharing (Fig. 4.3).

An effective supply chain risk management should consider these factors for implementing collaborative resource sharing as a standard risk management method. Therefore, we derive first recommendations based on the above-mentioned key success factors on how collaborative resource sharing could be implemented in practice. A collaborative sharing of risk information could be the starting point. Joint web platforms or software solutions offer the possibility to provide and share information between supply chain partners concerning possible impacts on supply chain disruptions such as where in the world happed an earthquake, a fire in a factory and what could be the possible impact on the supply chain, etc. could be monitored (Bendul & Brüning, 2017). Agreed procedures and guidelines following a standardized process could be the basis for all collaborative risk management activities. Especially in chaotic situations which require a fast decision-making which is the case when disruptive events happen, it could be helpful to follow a defined procedure. Therefore, agreed procedures such as responsibilities concerning decisions, information paths, etc. with the most important supply chain partners could be defined to enable fast decisions. This also facilitates joint decision-making cross company wide. Therefore, it would also be helpful that each supply chain partner defines the responsible person who should coordinate the supply chain risk management activities for this company. These responsible persons could form a special task force group that defines and coordinates the collaborative supply chain risk management activities in case of a disruption. Further, a collaborative performance management system could be implemented by the joint definition of relevant key performance indicators such as level of inventory, number of backup suppliers for fast-moving products, etc. for supply chain risk management. This should be implemented in the company-wide supply chain risk management process of each company and is also the basis for the joint sharing of risks and benefits. Trust and commitment could not be defined by rules and guidelines. This is the result of trustworthy work between the supply chain partners over years. Nevertheless, a framework like a code of conduct where the supply chain partners agree on their most important core values and their commitment to how they want to behave in disruptive situations could be a first step. To facilitate the possible resources which can be shared in case of a disruption it could be helpful that each supply chain partner defines the possible production and human resources. For the production resources, this can be easily summarized in a list of which factories are located where in the world with which machines, tools, etc. Further, this list can be used to make remarks on which of them can be shared and what are the prerequisites for sharing. Exemplarily, a drilling machine could be easily shared, also a punching tool could be transferred between factories whereas special tools such as a laser machine could not be easily transferred. For human resources, it would be helpful that each company defines a short profile of their employees concerning their skills. This facilitates to define the necessary persons depending on the disruptive event as to which resource can be shared.

Table 4.3 summarizes the proposed strategies for practitioners implementing a collaborative supply chain risk management.

Table 4.3 Recommendation strategies for implementing a successful collaborative supply chain risk management

Key success factors for successful collaborative risk management	Recommendation strategies for implementing collaborative risk management
Risk Information Sharing	Joint use of information channels concerning disruption events
Standardization of Procedures	Definition of cross company wide guidelines for decision-making and information paths
Joint Decision-Making	Definition of responsible task force person
Risk and Benefit Sharing	Definition of agreed level of risks and benefits
Process Integration	Integration of defined measures in the company-specific supply chain risk management activities
Collaborative Performance System	Joint definition of relevant cross company wide key performance indicators for supply chain risk management
Trust and Commitment	Definition of code of conduct
Resource Sharing	Definition of relevant production resources and skill profiles of possible human resources which can be shared

4.5 Discussion and Conclusion

The overarching goal of this research was to define how resource sharing enables supply chain disruption management.

The results of our survey confirm the practical relevance of collaborative resource sharing as a risk management method. Due to the increasing occurrence of disruptions which current developments such as the COVID pandemic has shown this need will enhance and companies have to think about collaborative answers to disruptions in order to maintain supply chain resilience (Ivanov & Dolgui, 2020; Ivanov, 2021; Ruel et al., 2021). At the same time, it has also been shown that there is a lot of untouched potential regarding the organization and planning of collaborative resource sharing which also Brüning et al. (2015) pointed out in their work. Ivanov (2021b) defined AURA (Active Usage of Resilience Assets) framework to increase supply chain resilience which can be seen as complementary concepts of a successful collaborative supply chain risk management.

Further, our survey demonstrates the sharing of human resources and production resources as a favorable collaboration. This is in line with the findings of the relational view theory of Dyer and Singher (1998) who state that the sharing increases benefits for all involved participants. Especially trust and commitment are central key factors for the willingness to collaborate to share resources. This confirms the growing importance of trust and commitment between supply chin partners described by Paluri and Mishal (2020) and also Cockx et al. (2019).

Our elaborated model regarding the most important categories reading a successful implementation of collaborative risk management makes important theoretical and practical remarks. First, it could serve as a framework for further research in the area of supply chain risk management for researchers. Especially, the relationship between each of the categories could make worthful contributions. Further the influence of environmental factors such as cultural aspects, technological developments etc. offers potential for further research. On the other hand, this framework gives an overview for practitioners about the most relevant factors which should be addressed in the design of collaborative risk management methods. This increases the awareness of the areas which should be covered for the implementation of collaborative resource sharing.

Although, our research makes several contributions some limitations must be considered. First, the participants of the survey mainly come from the german speaking area. Due to the growing interrelationship and globalization, the extension to more international participants would offer further value. Moreover, the research of the eight expert interviews could be extended to a wider set of experts coming from different branches and company sizes.

References

Agarwal, A. & Shankar, R. (2003). On-line trust building in e-enabled supply chain: Supply Chain Management. *An International Journal, 8*(4), 324–334. https://doi.org/10.1108/13598540310490080

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

Bendul, J., & Brüning M. (2017). *Collaborative supply chain risk management – new measures for managing severe supply chain disruptions*.

Bode, C., Wagner, S. M., Petersen, K. J., & Ellram, L. M. (2011). Understanding responses to supply chain disruptions: Insights from information processing and resource dependence perspectives. *Academy of Management Journal, 54*(4), 833–856.

Bovell, L. J. (2012). *Joint resolution of supply chain risks: The role of risk characteristics and problem solving approach*. Dissertation, Georgia State University. https://scholarworks.gsu.edu/marketing_diss/23

Brandon Jones, B., Squire, C., Autry, K., & Petersen, J. (2014). A contingent resource-based perspective of supply chain resilience and robustness. *Journal of Supply Chain Management, 50*(3), 55–73. https://doi.org/10.1111/jscm.12050

Brüning, M., & Bendul, J. (2017). Relational view on collaborative supply chain disruption recoveries. *Proceedings of the Hamburg International Conference of Logistics (HICL)*. https://doi.org/10.15480/882.1452

Brüning, M., Hartono, N., & Bendul, J. C. (2015). Collaborative recovery from supply chain disruptions: Characteristics and enablers. *Research in Logistics and Production, 3*(5), 225–237.

Burnson, P. (2019). https://www.scmr.com/article/global_supply_chain_risk_events_increased_36_in_2018_according_to_resilincs

Cao, M., Vonderembse, M., Zhang, Q., & Ragu-Nathan, T. S. (2010). Supply chain collaboration: Conceptualization and instrument development. *International Journal of Production Research, 48*(22), 6613–6635.

Cao, M., & Zhang, Q. (2013). *Supply chain collaboration*. Springer.

Carey, S., Lawson, B., & Krause, D. R. (2011). Social capital configuration, legal bonds and performance in buyer-supplier relationships. *Journal of Operations Management, 29*(4), 277–288.

Chen, I. J., Paulraj, A., & Lado, A. A. (2004). Strategic purchasing, supply management, and firm performance. *Journal of Operations Management, 22*(5), 505–523.

Chen, J. V., Yen, D. C., Rajkumar, T. M., & Tomochko, N. A. (2011). The antecedent factors on trust and commitment in supply chain relationships. *Computer Standards and Interface, 33*(3), 262–270.

Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management, 15*(2), 1–13. https://doi.org/10.1108/09574090410700275

Christopher, M., & Holweg, M. (2017). Supply chain 2.0 revisited: a framework for managing volatility-induced risk in the supply chain. *International Journal of Physical Distribution & Logistiks Management 47*(1), 2–17. https://doi.org/0.1108/IJPDLM-09-2016-0245

Cockx, R., Armbruster, D., & Bendul, J. C. (2019). Resource sharing as supply chain disruption risk management measure. *IFAC-PapersOnLine, 52*(13), 802–807. https://doi.org/10.1016/j.ifacol.2019.11.228

Duong, L. N. K., & Chong, J. (2020). Supply chain collaboration in the presence of disruptions: A literature review. *International Journal of Production Research, 58*(11), 3488–3507. https://doi.org/10.1080/00207543.2020.1712491

Dyer, J. H., & Singh, H. (1998). The relational view: Cooperative strategy and sources of interorganizational competitive advantage. *Academy of Management Review, 23*, 660–679.

Fortune. (2022). https://fortune.com/2022/03/14/china-shenzhen-lockdown-covid-foxconn-apple-supply-chain/

Friday, D., Ryan, S., Sridharan, R., & Collins, D. (2018). Collaborative risk management: A systematic literature review. *International Journal of Physical Distribution & Logistics Management, 48*(3), 231–253. https://doi.org/10.1108/IJPDLM-01-2017-0035

Guide, D., & Ketokivi, M. (2015). Notes from the Editors: Redefining some methodological criteria for the journal. *Journal of Operations Management, 37*, v–viii.

Ha, B. C., Park, Y. K., & Cho, S. (2011). Suppliers' affective trust and trust in competency in buyers: Its effect on collaboration and logistics efficiency. *International Journal of Operations and Production Management, 31*(1), 56–77.

Ivanov, D. (2018). *Structural dynamics and resilience in supply chain risk management*. Springer. ISBN 978-3-319-69304-0.

Ivanov, D. (2020). 'A Blessing in Disguise' or 'as if it Wasn't Hard Enough Already': Reciprocal and aggravate vulnerabilities in the supply chain. *International Journal of Production Research, 58*(11), 3252–3262. https://doi.org/10.1080/00207543.2019.1634850

Ivanov, D. (2021a). Supply chain viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. *International Journal of Production Research, 59*(12), 3535–3552.

Ivanov, D. (2021b). Lean resilience: AURA (Active Usage of Resilience Assets) framework for post-COVID-19 supply chain management. *International Journal of Logistics Management.*https://doi.org/10.1108/IJLM-11-2020-0448

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research, 58*(10), 2904–2915.

Kitano, H. (2004). Biological robustness. *Nature Reviews Genetics, 5*(11), 826–837. https://doi.org/10.1038/nrg1471

Lavie, D. (2006). The competitive advantage of interconnected firms: An extension of the resource-based view. *Academy of Management Review, 31*(3), 638–658.

Li, G., Fan, H., Lee, P. K. C., & Cheng, T. C. E. (2015). Joint supply chain risk management: An agency and collaboration perspective. *International Journal of Production Economics, 164*, 83–94. https://doi.org/10.1016/j.ijpe.2015.02.021

Marchese, K., & Paramasivam, S. (2013). Deloitte: The Ripple Effect: How manufacturing and retail executives view the growing challenge of supply chain risk.

McEvily, B., Perrone, V., & Zaheer, A. (2003). Trust as an organizing principle. *Organization Science, 14*, 91–103.

Melnyk, S. A., Davis, E. W., Spekman, R. E., & Sandor, J. (2010). Outcome-driven SCs. *MIT Sloan Management Review, 51*(2), 33–33.

Mohammed, L., Sahay, B., Sahay, V., & Abdul, W. (2010). Measuring trust in supply chain partners' relationships. *Measuring Business Excellence, 14*(3), 53–69.

Moorman, C., Deshpande, R., & Zaltman, G. (1993). Factors affecting trust in market research relationships. *Journal of Marketing, 57*(1), 81–101.

Munir, M., et al. (2020). "Supply chain risk management and operational performance: The enabling role of supply chain integration." International Journal of Production Economics 227.

Nyaga, G. N., Whipple, J. M., & Lynch, D. F. (2010). Examining supply chain relationships: Do buyer and supplier perspectives on collaborative relationships differ? *Journal of Operations Management, 28*(2), 101–114.

Paluri, R. A., & Mishal, A. V. (2020). Trust and commitment in supply chain management: A systematic review of literature. *Benchmarking: An International Journal, 27*, 2831–2862.

Pettit, T. J., Croxton, K. L., & Fiksel, J. (2013). Ensuring Supply Chain Resilience: Development and Implementation of an Assessment Tool. *Journal of Business Logistics, 34*(1), 46–76. https://doi.org/10.1111/jbl.12009

Piller, T. (2022). https://www.faz.net/aktuell/wirtschaft/unternehmen/bei-volkswagen-stehen-zwei-werke-still-17838335.html

Ruel, S., El Baz, J., Ivanov, D., & Das, A. (2021). Supply chain viability: Conceptualization, measurement, and nomological validation. *Annals of Operations Research*. https://doi.org/10.1007/s10479-021-03974-9

Sheffi, Y. (2005). *The resilient enterprise: Overcoming vulnerability for competitive advantage*. MIT Press.

Wagner, S. M., & Kemmerling, R. (2010). Handling nonresponse in logistics research. *Journal of Business Logistics, 31*(2), 357–381.

Whipple, J. M., & Russell, D. (2007). Building supply chain collaboration: A typology of collaborative approaches. *The International Journal of Logistics Management, 18*(2), 174–196.P\hspace*{-2pt}

Wieland, A., & Wallenburg, C. M. (2012). Dealing with supply chain risks: Linking risk management practices and strategies to performance. *International Journal of Physical Distribution & Logistics Management, 42*(10), 887–905.

Wieland, A., & Wallenburg, C. M. (2013). The influence of relational competencies on supply chain resilience: A relational view. *International Journal of Physical Distribution & Logistics Management, 43*, 300–320.

Chapter 5
Reconfigurable Strategies to Manage Uncertainties in Supply Chains Due to Large-Scale Disruptions

Towfique Rahman and Sanjoy Kumar Paul

Trusting that there is a next step is the first step to figuring out what the next step is. Jennifer Williamson

Abstract Global supply chains have been facing severe disruptions for the last decade. Large-scale disruptions are imposing unknown risks across the supply chain networks. These types of risks are unpredictable to assume the complexity, timing, and location of the occurrence and its simultaneously happening as businesses are challenged to operate in a volatile, uncertain, complex, and ambiguous (VUCA) environment. The COVID-19 pandemic has drastically disrupted the global supply chains, the impact of which is yet to know. Due to the time-to-time lockdown, shutdown, and border closure, global supply chains faced supplier failure, production capacity degradation, restrictions in transportations, and lack of sufficient inventory to meet the extra demand of the essential products. On the other hand, those manufacturers involved in producing luxury and low-demand products faced a huge demand fall. As a result of this, they struggled to continue their business. The long-established supply chains have been unable to manage large-scale supply chain disruptions caused by the COVID-19 pandemic. This study, thus, aimed to understand the uncertainties in supply chains in the wake of large-scale disruptions and to figure out the implications of reconfigurable strategies to manage uncertainties in supply chains due to large-scale disruption.

Keywords Supply chain · Risk · Uncertainty · Large-scale disruption · Strategy · Resilience

T. Rahman (✉) · S. K. Paul
UTS Business School, University of Technology Sydney, Sydney, Australia
e-mail: Towfique.Rahman@student.uts.edu.au; Sanjoy.Paul@uts.edu.au

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_5

5.1 Introduction

Reconfigurable strategies to manage uncertainties in supply chains (SCs) due to large-scale disruptions have attained significant importance to academicians and practitioners. Global supply chains have faced severe disruptions during the last decade (Blackhurst et al., 2018). Recently occurred COVID-19 pandemic has disrupted the global supply chains, the impact of which is yet to know (Sarmah, 2020). The uncertainties that the pandemic has imposed on the global supply chains have raised the question of the strength of resilience and sustainability of the existing supply chains of the businesses. Large-scale disruptions such as the COVID-19 pandemic have disrupted the demand, supply, and production capacity of the essential and non-essential products, respectively (M. T. Chowdhury et al., 2020). Most of the manufacturers are struggling to find out strategies to mitigate such disruptions caused by the COVID-19 pandemic; hence, disruption recovery planning is necessary to manage such future extraordinary supply chain disruptions (Zhu et al., 2020).

Within the domain of uncertainties of SC risks and disruptions, uncertainties of SC are mainly raised due to "micro risks" and "macro risks" (Munir et al., 2020). Supply chains face uncertainties due to micro risks mainly because of day-to-day operational risks such as sudden supply failure, production shutdown, lead time change, delivery delay because of the scarcity of transportation, etc. (Sabouhi et al., 2018). The reasons behind the uncertainties due to macro risks are mainly large-scale disruption risks such as natural catastrophes, epidemic outbreaks, pandemic, etc. (Aldrighetti et al., 2019). The recently occurred COVID-19 pandemic can be referred to as super disruptions (Ivanov & Das, 2020). Some researchers have defined this global pandemic as extraordinary disruptions (Paul & Chowdhury, 2020b). The majority of the SC disruption literature has focused on risk identification, assessment, and mitigation to date, while minimal research considers developing reconfigurable strategies to mitigate uncertainties in supply chains due to large-scale disruptions such as the COVID-19 pandemic. Planning to adopt reconfigurable strategies to manage uncertainties in supply chains is necessary to strengthen their resilience and sustainability in the wake of large-scale supply chain disruptions (Ivanov & Sokolov, 2013). Many firms and supply chains can identify the risks and make an assessment, but most manufacturers of essential items struggle to execute reconfigurable strategies to manage uncertainties in supply chain due to large-scale supply chain disruptions.

This chapter focuses on the following aims considering the lack of research regarding planning to adopt reconfigurable strategies to manage uncertainties in supply chain due to large-scale disruptions:

1. To understand the uncertainties in supply chains in the wake of large-scale disruptions.
2. To figure out the implications of reconfigurable strategies to manage uncertainties in supply chains due to large-scale disruption.

The long-established supply chains have been unable to manage large-scale supply chain disruptions caused by the COVID-19 pandemic (Paul et al., 2022). The threat and vulnerabilities that the global pandemic has imposed on the global supply chains have raised the importance to execute reconfigurable strategies to manage uncertainties in supply chains by strengthening resilience and the sustainability of the current supply chains of the global businesses (Remko, 2020). Hence, the objective of this study is to understand the sources of supply chain uncertainties and vulnerabilities, their impacts, and implications of the reconfigurable strategies as a part of planning to manage large-scale disruptions and find out the potential research gaps and future research directions.

5.2 SC Uncertainties, Sources, and Impacts

In this section, we briefly review the studies of uncertainties in supply chain, sources of supply chain uncertainties, supply chain uncertainties due to large-scale disruptions and their impacts, and planning and reconfigurable strategies to manage supply chain uncertainties in the light of previous research conducted in the literature. Potential research gaps are also highlighted in this section.

5.2.1 Uncertainties in Supply Chains (SCs)

Uncertainties in supply chains are referred to as the changes of balance and profitability of the supply chains due to potential unpredictable incidents, which require a response to re-establish the change of balance (Singh et al., 2019). Potential unpredictable incidents can be unexpected order, huge demand surge, late delivery from the supplier, breakdown of a critical component in production units, etc. (Remko, 2020). Uncertainties in supply chain initiate risks. Micro and macro disruptions cause uncertainties in supply chains. Macro disruptions such as natural calamity, geo-political instability, terrorist attack, epidemic, pandemic impose huge uncertainty in supply chains (Zainal Abidin & Ingirige, 2018). Uncertainties induce risks and that turns into disruptions in supply chains. There are several reasons that influence the deviation of the planned structure of the supply chains. There can be two kinds of influences of deviations that lead to supply chain uncertainties, i.e., (1) influence of purposeful deviation and (2) influence of non-purposeful deviation (Ivanov & Sokolov, 2010). Theft, terrorism, financial misleads, etc. are the influences of purposeful deviation. Whereas influences of non-purposeful deviation can be environmental, economic, or technological. Examples of influences of non-purposeful environmental deviations are natural calamities, epidemics, or pandemics such as the recently occurred COVID-19 pandemic, etc. Supply–demand fluctuations and bull-whip effects are examples of influences of non-purposeful economic deviations (Bier et al., 2020).

From the literature it is found that there are two types of uncertainties that affect supply chains the most: (1) risks from supply and demand problems and (2) risks from purposeful disruptions to normal supply chain activities (S. Xu et al., 2020a). Supply chains face demand, supply, manufacturing, transportation, and delivery, technical, and financial risks due to the purposeful and non-purposeful influences of uncertainties. In the next section, the sources of supply chain uncertainty and vulnerability are discussed.

5.2.2 Sources of SC Uncertainty and Vulnerability

In the extant literature, researchers have identified lots of sources of uncertainties in supply chains that lead to risks, disturbances, and disruptions. In Fig. 5.1, a summary of the sources of uncertainties in supply chains is presented from the literature.

The sources of uncertainties in supply chains can be divided into three parts: (1) internal organization uncertainty, (2) internal sources of supply chain uncertainties, and (3) external sources of uncertainties (Hasani & Khosrojerdi, 2016). The sources of uncertainties in supply chains mentioned in Fig. 5.1 are all related to internal and external sources of uncertainties. The details of the sources of uncertainties are explained below:

5.2.2.1 Environmental Uncertainties

Environmental uncertainty refers to unpredictable changes that occur externally. These external changes cause instability in the environment of the regular businesses, the degree of which is hard to understand, estimate and make sense (Fazli-Khalaf et al., 2020). The supply chains of the businesses can not merely understand how an external environment might change, the potential impact of the changes, and what strategies they might initiate to manage the changes and make

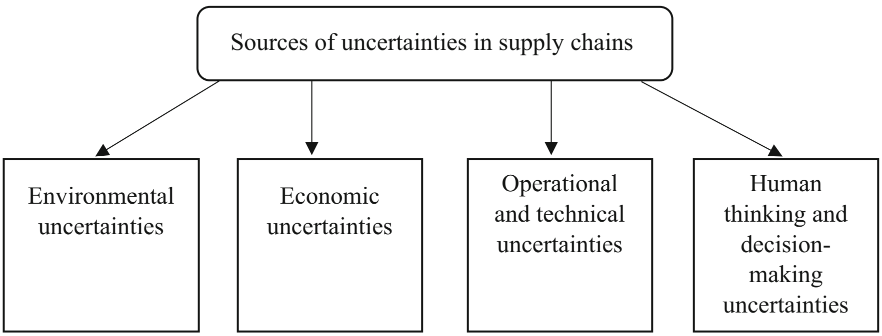


Fig. 5.1 Classifications of the sources of uncertainties in supply chains (Ivanov & Sokolov, 2010)

a balance within the supply chain networks. Environmental uncertainties consist of natural uncertainties, behavioral uncertainties, and goal uncertainties (Ivanov & Sokolov, 2010). Uncertainties regarding the reliability of the suppliers, variations in the choices and behaviors of consumers, the uncertain actions of the competitors, changes in the quality of the products, volatility in inter-firm relationships, etc. are all examples of environmental uncertainties in supply chains (Ang et al., 2017). That is why dynamic environments may be characterized by changes in product demand and supply, changes in consumer choices and preferences, changes in technology, etc. (Kamalahmadi & Parast, 2017). Environmental changes should never be ignored within supply chain networks. In summary, major sources of environmental uncertainties within supply chain networks are consumers (demand), suppliers (supply), technology (infrastructure), and competitors (Li & Zobel, 2020). All these environmental uncertainties induce uncertainties in demand, supply, manufacturing process, and control within supply chain networks.

5.2.2.2 Economic Uncertainties

Internal and external economic uncertainties are major sources of uncertainties within supply chain networks. Changes in the inflation rate, world economic recession, internal loss are all examples of economic uncertainties in the supply chains (Açikgöz & Günay, 2020). In the global context, global shutdown impacted by USA/China trade war, Brexit, global lockdown, and shutdown due to pandemic caused by COVID-19 posed severe economic impact on the global supply chains (Fornaro & Wolf, 2020; Ivanov & Sokolov, 2013; Yaya et al., 2020). Businesses cannot control everything outside the organizations. Supply chains of the businesses should be strategic, flexible, and dynamic in responding to external changes that might give a timely solution.

5.2.2.3 Operational and Technical Uncertainties

Supply chains of businesses face various internal operational and technical uncertainties. Day-to-day production failure due to technical insufficiency and problems, production failure due to lack of experience of the operators, etc. are examples of operational and technical uncertainties of supply chains (Soren & Shastri, 2019). Operational and technical uncertainties sometimes may cause a capacity shortage for which the manufacturers become unable to fulfill the demand surge of the consumers. This condition increases the shortage costs of the supply chains (Priya Datta et al., 2007). Manufacturers need to invest more in high-tech to foster the manufacturing process that may deal with the operational and technical uncertainties timely.

5.2.2.4 Human Thinking and Decision-Making Uncertainties

Human thinking and decision-making uncertainties are other sources of uncertainties in supply chains. Weak coordination, weak control of logistics, weak decision-making capability, lack of knowledge of the top management, a late decision from the top management, etc. are all examples of human thinking and decision-making uncertainties (Li & Zobel, 2020; Remko, 2020, Ardolino et al., 2022). In this time of artificial intelligence, human knowledge is also very important. Without the proper guidance of human intelligence, artificial intelligence in supply chains may lead to disasters (Dwivedi et al., 2019). So, human intelligence and better decision-making capabilities are very important to manage supply chain uncertainties.

Uncertainties initiate risks, disturbances, deviations, and disruptions in supply chains. To mitigate the supply chain disruptions, practitioners need to have a good understanding of the sources of supply chain uncertainties. In the next section, we discuss the supply chain uncertainties that might arise from large-scale disruptions.

5.2.3 SC Uncertainty Due to Large-Scale Disruptions

Large-scale disruptions cause unlimited supply chain uncertainties. The recently occurred pandemic caused by the COVID-19 pandemic can be taken as an example to understand how large-scale disruptions cause uncertainties in supply chains. The COVID-19 pandemic has drastically impacted the global supply chains, the impact, and uncertainties of which are yet to know (Cai & Luo, 2020). The COVID-19 pandemic has imposed environmental uncertainties, economic uncertainties, operational and technical uncertainties, and human thinking and decision-making uncertainties for the supply chains of the businesses of the world.

Environmental uncertainties due to large-scale disruption have impacted the global supply chains the most. Most of the countries of the world imposed strict lockdown and shut down inside the country and restricted the border to a large extent. Some countries of the world like Australia closed the border with almost all the countries with a very limited exemption (Antony et al., 2020). This strict restriction has imposed a severe impact on the supply of goods from the source of one country to the manufacturer of another country. The manufacturers of essential products such as food, personal protective equipment, etc. faced severe supply shortages (Poudel et al., 2020). As a result of this, fear spread among the general people about the shortage of essential products. People panic purchased essential products such as food, toilet paper, etc. and the retailers struggled to meet the demand surge (Nicola et al., 2020). The pandemic also proved that the current technology of the manufacturing units was not capable to increase the production to meet the extra demand of the consumers. Thus, large-scale disruption caused by COVID-19 has imposed severe environmental uncertainties on the global supply chains.

Due to the lockdown and shutdown to control the spread of the COVID-19 virus, the economic activities of the world slowed down which turned into a severe global economic recession (Fernandes, 2020). The supplier failed to deliver the products to the manufactures, because of this, the manufacturers could not ramp up the production capacity to fulfill the demand of the consumers. The supply chains of most of the industries faced an increased shortage cost (Mehrotra et al., 2020). Thus, the large-scale disruption caused by COVID-19 impacted the turnover of the industries.

The current operational and technological strength of the manufacturers could not allow them to ramp up the production capacity to meet the demand surge, especially the demand of the essential products of the consumers. Thus, the weakness of the operational capacity and technological condition are the major uncertainties in supply chains induced by the COVID-19 pandemic (Z. Xu et al., 2020b).

Moreover, the decision-makers of the industries struggled to adopt strategies to manage all levels of environmental, economic, operational, and technological uncertainties caused by the pandemic to bring balance in the supply chains. The impacts of the pandemic are beyond normal human thinking; because of this, decision-makers got puzzled to adopt any reconfigurable strategies to manage the impacts of the large-scale disruptions (Li et al., 2020). In the next section, we discuss the impacts of uncertainties in supply chains due to large-scale disruptions.

5.2.4 Impacts of Uncertainties in SCs Due to Large-Scale Disruptions

Uncertainties due to large-scale disruption such as the COVID-19 pandemic have drastically impacted the global supply chains, the severity of which is yet to know. Nevertheless, the overall understanding of the impacts of the disruptions on the supply chains is very important to formulate reconfigurable strategies to manage the impacts successfully. The following texts present the impacts of uncertainties due to large-scale disruption on the supply chains.

5.2.4.1 Impact on Demand Management

During the pandemic, the global supply chains faced severe demand fluctuation of the high demand products and low-demand products as well. Suppliers failed to provide raw materials to the manufacturers in other countries, because of this, the manufacturers could not ramp up the production capacity to meet the demand surge of the consumers for high-demand products such as food, toilet paper, personal protective equipment, facemask, etc. (Mehrotra et al., 2020). People panic purchased the high-demand essential products that caused severe stockout of the products in the super shops. Along with this, the demand of the low-demand luxury products dropped as the economic activities slowed down due to lockdown and shutdown conditions. COVID-19 created a severe level of demand disruption (Ivanov & Das, 2020).

5.2.4.2 Impact on Supply Management

Most of the countries of the world imposed strict restrictions on the borders, imposed lockdown, and shut down inside the country to flatten the curve of COVID-19 infected cases. Because of this strict restriction, manufacturers struggled to receive raw materials from suppliers situated in quarantined zones (P. Chowdhury et al., 2021). Many manufacturers have only one supplier from one geographical location. The pandemic has impacted those manufacturers who have a single supplier and suppliers in quarantined zones (M. T. Chowdhury et al., 2020). These supply disruptions impacted the manufacturing facilities. They could not increase the production capacity to meet the demand surge of the consumers (Cai & Luo, 2020). Thus, supply disruptions drastically impacted the whole supply chain network.

5.2.4.3 Impact on Production Management

Due to supply and demand disruptions, the manufacturers could not accelerate the production capacity. Many industries had to forcefully shut down the operations of manufacturing due to severe loss and debt (Li et al., 2020). Most of the manufacturers could not upgrade the infrastructure to facilitate the employees to continue their work as a strict guideline for social distance was imposed by the government of most of the countries to stop the spread of the virus. The manufacturing industries also lost goodwill as they could not fulfill the extra demand of essential products of the consumers (Mehrotra et al., 2020).

5.2.4.4 Impact on Transportation and Delivery Management

Timely delivery of the ordered products to the consumers is essential for the supply chains of the businesses to get rid of the backlog of the orders and associated costs. Maintaining goodwill is another important issue for businesses by delivering products to consumers timely. Unfortunately, due to lockdown and shutdown conditions in most of the countries, two things happened with respect to transportation and delivery. First, those businesses who were related to the high demand and essential product struggled to maintain quick delivery to the consumers because of shortage of products due to low production capacity of the manufacturers and strict lockdown situation because of increasing COVID-19 infection cases (Guan et al., 2020; Li et al., 2020). And if they somehow managed to increase the production capacity, they could not deliver the extra products to the consumers timely due to lack of transportation capacity (Sarmah, 2020). Secondly, those businesses who were related to low-demand luxury products their transportation and logistics support faced a downgrade of business because the demand of such luxury products dropped significantly. In both cases, transportations and logistics businesses faced severe disruptions (Queiroz et al., 2020).

5.2.4.5 Impact on Information Management

Information related to the supply chain dynamics is very important in businesses based on which decision-makers decide to solve disruptions related to supply chains (Govindan et al., 2020). The demand of essential products increased because of fear of lockdown due to the COVID-19 pandemic. Current global supply chains of the essential products struggled to get the information related to the exact demand of the consumers because of a lack of dynamic demand forecasting capability, technology, and infrastructure, which largely impacted the information management of the current global SCs (Ivanov, 2020b; Remko, 2020). Moreover, decision-makers could not take a timely decision to recover the supply chains due to lack of information regarding the extraordinary disruption caused by the COVID-19 pandemic.

5.2.4.6 Impact on Financial Management

Supply chains of the manufacturers worldwide faced severe supply and demand disruptions throughout the pandemic caused by COVID-19. Manufacturers could not ramp up production capacity to meet the extra demand of the essential products of consumers. As a result of this, essential product's manufacturers faced severely increased shortage costs (Zhu et al., 2020). On the other hand, as the demand of luxury products declined, many of the manufacturers of luxury products had to limit the production that affected their revenue. During extreme lockdown cases because of community transmission of COVID-19 infections, the manufacturers of the businesses had to shut down their production for a while that affected their SC financial conditions severely (Cai & Luo, 2020). Thus, large-scale disruption impacted the financial management of the global supply chains extremely.

5.2.4.7 Impact on SC Sustainability Performance

COVID-19 pandemic has largely impacted all levels of supply chain networks, the impacts of which have severely downgraded sustainability performances of the global supply chains (Sharma et al., 2020). Environmental performances of the essential product manufacturers were severely affected. The essential manufacturers of personal protective equipment such as facemask had to increase their production capacity to meet the consumer demand (Wu et al., 2020). The government of most of the countries imposed strict regulations for the people to wear a facemask to get rid of the COVID-19 virus as per the guideline published by the world health organization (WHO) (Song & Karako, 2020). As a result of this, the waste of used facemask and other personal protective equipment increased drastically, which has impacted the environment heavily (Queiroz et al., 2020). Due to the lockdown and shutdown situation, the supply chains faced increased shortage costs, and thus large-scale disruption caused by the pandemic impacted the economic performance of the supply chains. Many employees lost their jobs due to the permanent shutdown of many manufacturers of the world due to the drastic disruption and world economic recession caused by the pandemic. Thus, the social performances of the supply chains of the manufacturers were impacted (Taqi et al., 2020). The reputation of most of the manufacturers was hampered as they could not ramp up their production capacity to meet the extra demand of the consumers when people panic purchased essential products. Thus, the goodwill of the businesses was severely hampered (P. Chowdhury et al., 2021).

5.2.5 Planning and Strategies for SC Uncertainties and Observations

In the literature, many researchers have focused on resilience strategies, sustainable strategies, etc. as a part of planning to manage impacts on supply chains due to uncertainties caused by large-scale supply chain disruptions. Recovery planning to manage large-scale disruptions has gained much attention to academicians and practitioners. Other resilience strategies such as response and preparedness strategies have also been focused on by the majority of the researchers. Most of the resilience strategies were designed to manage short-term to long-term supply chain disruptions, very few of them focused on strategies for the reconfiguration of the supply chains (Alix et al., 2019). Reconfigurable strategies are those strategies that help to reconfigure the supply chains to sustain in an extreme disrupted situation such as the COVID-19 pandemic (Dolgui et al., 2020). In literature, the theme of reconfigurable strategies has not been focused on widely. The COVID-19 pandemic has proved that the current global supply chains need a redesign to sustain any future extraordinary disruption (Ortega-Jimenez et al., 2020). Decision-makers need to adopt reconfigurable SC strategies to make SCs more resilient and sustainable. Adaptation strategies for reconfiguring supply chains in the wake of large-scale supply chain disruptions to bring supply chains to a new normal state can be based on the adaptation strategies segmented by Ivanov (2021b), which is presented in Table 5.1. In the next section, we discuss the reconfigurable strategies for the supply chain networks that will aid to manage large-scale SC disruptions.

Table 5.1 Adaptation strategies for supply chain reconfiguration capabilities (Ivanov, 2021b)

Viable supply chain layers	Adaptation strategies			
	Intertwining	Substitution	Scalability	Re-purposing
Ecosystem	Intertwining of different supply chains			
Network		Structural network reconfiguration	Network size scalability	Process flexibility by re-purposing of flows
Resources		Product substitution	Capacity expansion at firm's resources	Products flexibility by re-purposing of resources

5.3 Reconfigurable Strategies to Manage SC Uncertainties Due to Large-Scale Disruptions

In this section, we focus on discussing the implications of the reconfigurable strategies to manage SC uncertainties due to large-scale disruptions such as the COVID-19 pandemic.

5.3.1 Reconfigurable Strategies to Manage Demand Uncertainties

Demand volatility happens when the need for essential items such as food, personal protective equipment rises due to emergencies such as the COVID-19 pandemic. In the time of the super disruption, the manufacturers of essential items struggle to scale up production due to a shortage of raw materials. Increasing production capacity by increasing emergency sourcing and by other vertical and horizontal collaborations may aid the manufacturers to avoid demand uncertainties (Rahman et al., 2021). Repurposing production by unlocking new production capacity can help to timely adopt strategies to fulfill the demand of the consumers (Rahman et al., 2021). The garment industry may face demand fall of the fashion and apparel items due to lock down and shut down of economic activities, in this case, they can switch their production facilities to produce personal protective equipment and facemask to alleviate the spread of infectious viruses in the time of super disruption like the COVID-19 pandemic to make their supply chains viable (Ivanov, 2020a).

5.3.2 Reconfigurable Strategies to Manage Supply Uncertainties

Uncertainties in the supply side are reasons for major disruption within supply chain networks. In the time of super disruption like the COVID-19 pandemic, strategies like having backup sourcing, multiple sourcing, and opportunities of local sourcing will aid to sustain the supply side of the supply chains (Dolgui et al., 2018). Keeping strategic stock or inventory stock are suggested by many researchers to avoid stockout situation during disruption (P. Chowdhury et al., 2021). Supplier segmentation will give a clear idea of the vulnerabilities associated with the suppliers. Manufacturers can re-structure their supplier selection based on the vulnerabilities (Ivanov, 2021a).

5.3.3 Reconfigurable Strategies to Manage Production Uncertainties

Dependence on a single offshore production facility for an efficient supply chain poses uncertainty in production capacity during super disruption like the COVID-19 pandemic. Researchers are suggesting more focus on back shoring, nearshoring, and increasing domestic production capability to make the supply chains more robust (P. Chowdhury et al., 2021). In the case of total nearshoring or localized production, there remain some uncertainties such as manufacturers still may need to depend on offshore suppliers for some critical components. Having multiple supplier options may aid to solve this problem during any disruptive situation. Manufacturers need to repurpose their production facilities by product diversification, substitution, and postponement to accelerate production capability to avoid uncertainties (Ivanov, 2021b). Decentralized additive manufacturing capability with product line flexibility and modularization may aid the supply chains to face production uncertainties (Pavlov et al., 2019). Decision-makers of the manufacturers can make a yearly contract with other manufacturing facilities so that during extraordinary disruption, they can continue their production to fulfill consumers' needs. During super disruption like the COVID-19 pandemic, manufacturers can utilize their idle capacity of essential products like healthcare products to increase production capacity to tackle any emergency (Ivanov, 2021a). Finally, decision-makers can focus on building industry 4.0 enabled manufacturing capability with human-robot collaboration to make the supply chains more viable (Luthra et al., 2011).

5.3.4 Reconfigurable Strategies to Manage Transportation and Delivery Uncertainties

In the time of super disruption like the COVID-19 pandemic, simultaneous supply, demand, and transportation disruptions impose many uncertainties in the supply chain network. It is imperative to collaborate with other transporters for emergency distribution planning to increase robustness to deliver the essential items to the consumers by creating multimodal and multi-route shipments during disruptions (Gunasekaran et al., 2015). Establishing more distribution centers and backup facilities as preparedness strategies will help to sustain logistics even in a disruptive situation (Aldrighetti et al., 2021). Establishing omni-channel distribution systems will help to continue material flow in time of disruptive situation (Ishfaq et al., 2021).

5.3.5 Reconfigurable Strategies to Manage Information Management Uncertainties

It is very important to sustain the information management of supply chains to avoid any kind of uncertainties. To secure the information, adopting blockchain technology and advanced tracking system, and enterprise resource planning capabilities is important (Durach et al., 2021). Big-data analytics will help the decision-makers to understand any challenges and bottlenecks within supply chains to avoid uncertainties (Ivanov, 2017). Digital supply chain twin will allow the businesses to adapt to any disruptive situation (Ishfaq et al., 2021).

5.3.6 Reconfigurable Strategies to Manage Financial Uncertainties

In the time of large-scale supply chain disruptions, instead of single disruption, multiple level disruptions happen within supply chains, i.e., simultaneous supply, demand, and transportation disruptions. Such long-term simultaneous disruptions create a financial crisis within supply chains. The public-private partnership helps to get enough financial support to sustain and resume supply chain activities during large-scale disruption such as the COVID-19 pandemic (Papadopoulos et al., 2017). Reserving liquidity can be considered as a preparedness strategy to avoid any future financial uncertainties within supply chains (Ivanov & Sokolov, 2019).

A summary of the reconfigurable strategies to manage SC uncertainties due to large-scale disruptions is presented in Table 5.2.

Table 5.2 Reconfigurable strategies to manage SC uncertainties due to large-scale disruptions

Level of uncertainties	Reconfigurable strategies	Application to reconfigure current SC to manage uncertainties	Reference
Demand uncertainties	Increasing production capacity	When there is a demand surge of essential items, increasing production capacity may aid to fulfill consumers' demand.	Rahman et al. (2021)
	Increasing emergency sourcing	Increasing emergency sourcing will aid to increase production capacity to meet the demand surge.	Ivanov (2020a)
	Unlock new production capacity	Repurposing production will unlock opportunities to produce other items to meet the demand of time. For example: suppliers in the automotive sector are at the same time producers of valves for respirators during the COVID-19 pandemic to meet extra healthcare demand.	Rahman et al. (2021)
	Horizontal and vertical collaboration	Resource sharing can be easily done by horizontal and vertical collaboration to enhance sourcing and production to meet consumers' demand, especially in the time of super disruption like the COVID-19 pandemic.	Ivanov (2020a)
Supply uncertainties	Backup sourcing	Backup sourcing helps to continue supply in case of a primary supplier failure.	Dolgui et al. (2018)
	Multiple sourcing	Having multiple suppliers help to enhance supply flexibility from a wider supplier base.	Dolgui and Ivanov (2021)
	Local sourcing	Local sourcing helps to enhance higher supply flexibility at lower transportation costs that may create robust redundancy in case of global super disruptions like the COVID-19 pandemic.	Ivanov (2021b)
	Supplier segmentation	Supplier segmentation helps to identify critical suppliers and helps to develop an emergency plan.	Ivanov (2021a)
	Strategic stock/Risk inventory	To meet the fluctuating demand of consumers and to get rid of stock-out, strategic stock/risk inventory may aid.	P. Chowdhury et al. (2021)

Production uncertainties	Reshoring/back shoring	Reshoring and back shoring help to reduce vulnerability and increase robustness which happens in the time of super disruptions like the COVID-19 pandemic.	Dolgui and Ivanov (2020)
	Nearshoring and domestic production	Similarly, nearshoring, and domestic production helps to reduce production vulnerability and increase robustness during disruptions.	P. Chowdhury et al. (2021)
	Repurposing	Repurposing helps to initiate quick demand-supply re-allocation by changing the production system and supply base.	Ivanov (2021b)
	Product diversification and substitution	Producing a large number of alternative items may aid to fulfill the extra demand during any disruption.	Paul and Chowdhury (2020a)
	Postponement	Postponement helps the manufacturers to quickly respond to unpredictable customer demand and improve inventory efficiency.	Tarafdar and Qrunfleh (2017)
	Decentralized manufacturing systems	Decentralized manufacturing facilities increase robustness during super disruption like the COVID-19 pandemic.	Pavlov et al. (2019)
	Product line flexibility and modularization	Helps to respond to fluctuating consumers' demand during disruptions.	Manuj et al. (2014)
	Sub-contracting facilities	Sub-contracting helps to continue production in the time of primary manufacturing facility disruption.	Ivanov (2019)
	Utilize idle capacity	Allows producing emergency products.	Ivanov (2021a)
	Additive manufacturing	Allows balancing supply–demand fluctuation by creating alternative products and services.	Ivanov (2021b)
	Industry 4.0	Robotic-enabled smart production facilities help to control production and scheduling based on real data by digital twins.	Luthra et al. (2011)
	Human-Robot collaboration	Robot-enabled manufacturing can be adopted in collaboration with human skills and intelligence to enhance production capacity even in the time of super disruptions such as the COVID-19 pandemic.	Ivanov (2021a)

(continued)

Table 5.2 (continued)

Level of uncertainties	Reconfigurable strategies	Application to reconfigure current SC to manage uncertainties	Reference
Transportation and delivery uncertainties	Collaboration with other transporters	Collaboration with other transporters during super disruption helps to enhance robustness in the delivery of products to the retailers and consumers.	Gunasekaran et al. (2015)
	Establish more distribution centers	More distribution centers close to customer zones help to increase resilience in logistics and ensure smooth delivery in the time of disruptive situation.	Paul et al. (2017)
	Multimodal and multi-route shipments	During disruption to make delivery smooth, multimodal and multi-route shipments allow to change transportation plan with the alternative route or alternative mode of transport.	Ivanov (2021a)
	Backup facilities	Backup facilities help to continue the distribution process even after the disruption in primary warehouse disruption.	Aldrighetti et al. (2021)
	Emergency distribution planning	Emergency distribution planning allows collaborating the emergency supply chain (i.e., healthcare, food supply chain) with the commercial supply chain to plan for an emergency delivery.	P. Chowdhury et al. (2021)
	Omni-channel	Omni-channel helps to continue material flow by changing distribution channels.	Ishfaq et al. (2021)
Information management uncertainties	Implementing blockchain technology and advanced tracking system	Helps to create supply chain visibility, disruption identification, and recovery support.	Durach et al. (2021)
	Integrating enterprise resource planning (ERP)	ERP helps to integrate internal and external supply chains to create more visibility.	Rahman et al. (2021)
	Big-data analytics	Big-data analytics help to extract data for continuous monitoring, risk, and opportunity mapping within supply chains.	Ivanov (2017)
	Digital twin	Allows creating a virtual model of a physical supply chain, forecasting model, and design adaptation through a cyber-physical system.	Ishfaq et al. (2021)
Financial management uncertainties	Public-private partnership	Government aid during disruptions helps to overcome supply chain financial uncertainties.	Papadopoulos et al. (2017)
	Reserve liquidity	Keeping reserve liquidity allows the business to continue chain activities even in super disruptions like the COVID-19 pandemic.	Ivanov and Sokolov (2019)

5.3.7 Reconfigurable Strategies for Supply Chain Sustainability

Reconfigurable strategies are designed to make the supply chains more resilient. An efficient supply chain is cost-effective. On the other hand, a resilient supply chain may not be cost-efficient but in the long run, a resilient supply chain saves businesses from disruptions. researchers are talking about a viable supply chain that ensures both resilience and sustainability (Ivanov, 2021b). Reconfigurable strategies can help the supply chain to be more resilient and sustainable for a robust and viable supply chain. In the time of large-scale disruptions, simultaneous disruptions in various levels of supply chains, i.e., simultaneous supply, demand, and logistics disruptions may happen (Rahman et al., 2021). For example, in the time of the COVID-19 pandemic, all sectors of supply chains were disrupted. Due to supply, demand disruption, manufacturers of essential products such as personal protective equipment, facemask, food, etc. scaled up production to meet the consumers' demand (Paul & Chowdhury, 2020a). As a result of this, many countries of the world have faced a huge surge in waste of such essential products like facemask that has hugely impacted the environment. Reconfigurable strategies are needed to maintain social, environmental, and economic performances of the supply chains to make the supply chains more viable. Some of the important reconfigurable strategies to make the supply chains more sustainable are presented in Table 5.3.

5.4 Modeling Methods for the Evaluation of the Strategies

Researchers have used various kinds of modeling methods to justify the strategies to make the supply chains more resilient, sustainable, and viable. Ivanov and Dolgui (2021) have categorized modeling approaches that have been used so far in the literature to aid in network-wise analyzing, planning decisions, process control and thus justifying strategies to make supply chains more resilient and sustainable. Table 5.4 presents the modeling methods catheterized by Ivanov and Dolgui (2021). For network-wide analysis and finding out bottlenecks in the supply chain networks, Bayesian networks, Complexity theory, Reliability theory, Petri nets, Markov Chains, etc. can be used. For planning decisions, mathematical optimization is considered better modeling method. On the other hand, for process control analysis various simulation methods rule. For a better understanding of the impacts of large-scale disruptions on the supply chains, and evaluation of the process decision-making strategies, mixed methods of mathematical optimization and simulation methods can immensely help to develop models for viable supply chains.

Table 5.3 Reconfigurable strategies to manage SC sustainability performance

SC sustainability performance	Reconfigurable strategy	Application	Reference
Social performance	Fulfilling consumers' demand	In the time of super disruption, fulfilling consumers' extra demand (induced by panic buying) helps to sustain the social performance of the supply chain.	Ghosh and Shah (2015)
	Increasing production capacity	Increasing production capacity ensures to fulfill consumers' demand.	Rahman et al. (2021)
	Ensuring health and safety issues across supply chains	During super disruptions like the COVID-19 pandemic, ensuing health and safety issues across supply chains help to sustain the social performance of the supply chain.	Ivanov (2021b)
Environmental performance	Increasing usage of organic/biodegradable product	Increasing biodegradable or organic product manufacturing capacity helps to sustain the environmental performance of the supply chain.	Vilarinho et al. (2018)
	Waste management and circular economy	Circular economy, revere logistics, and waste management capacity enhancement ensures the better environmental performance of the supply chain.	Pivnenko et al. (2016)
	Green production	Green production capacity sustains the environmental issues of supply chain.	Hsu et al. (2013)
	Reducing carbon emission	Reducing carbon emission measures ensures better environmental sustainability across the supply chain, especially for the transportation side.	Aldrighetti et al. (2021)

Economic performance	Reducing shortage costs	Reducing shortage costs by fulfilling consumer demand and order quickly helps to enhance the economic performance of the supply chain.	Rahman et al. (2021)
	Maximize profit	Maximize profit by reducing total supply chain costs and business diversification helps to sustain the economic performance of the supply chain.	Shahed et al. (2021)
	Increase sharing resources	During super disruptions like the COVID-19 pandemic, increasing sharing resourcing by vertical and horizontal collaboration helps to sustain economic performance.	Mehrotra et al. (2020)
	Increase sharing economy	Sharing financial resourcing among vertical supply chains and other horizontal organizations helps to sustain economic performance even in the super disruption like the COVID-19 pandemic.	Pettit et al. (2019)
	Resume and continue supply chain activities	Super disruptions like the COVID-19 pandemic disrupt the supply chains resulting in partial and full closure of the production facilities for a certain period. Taking immediate measures to resume supply chain activities by adopting recovery measures helps to sustain economic disruptions within supply chains and businesses.	Rahman et al. (2021)

Table 5.4 Modeling methods to justify supply chain reconfigurable strategies (Ivanov & Dolgui, 2021)

Network and complexity theories	Mathematical optimization	Simulation
Bayesian networks Complexity theory Reliability theory Petri Nets Markov Chains	Mixed-integer linear programming Robust optimization Stochastic optimization	Agent-based simulation Discrete-event simulation Systems dynamics
Network-wise analysis	*Planning decisions*	*Process control*

5.5 Conclusions

Global supply chains have faced enormous disruptions during the last two decades. Recently the COVID-19 pandemic has drastically disrupted the global supply chains, the impact of which is yet to know. Decision-makers need to adopt timely measures to sustain their supply chains. To make the supply chains resilient and sustainable, decision-makers need to adopt the appropriate reconfigurable strategies to align their supply chains during disruptive events. The managers of the supply chains need to identify a set of supply chain reconfigurable and dynamic strategies that can help the supply chains to recover from super disruptions. Super disruptions like the COVID-19 pandemic cause simultaneous disruptions to different levels of supply chains the impact of which is totally unknown. Unknown-unknown uncertainties caused by the pandemic can be handled by adaptation strategies like scalability, substitution, repurposing, and intertwining strategies (Ivanov, 2021b). So, identifying and measuring uncertainties within supply chains is important. Adopting reconfigurable strategies to mitigate those uncertainties caused by large-scale disruptions is important to make the supply chains viable. Researchers can adopt various modeling methods to justify the reconfigurable strategies to make the supply chains more resilient and sustainable. They can test the strategies and develop significant changes in the dynamic of the strategies to make the supply chains more viable.

References

Açikgöz, Ö., & Günay, A. (2020). The early impact of the Covid-19 pandemic on the global and Turkish economy. *Turkish Journal of Medical Sciences, 50*, 520–526. https://doi.org/10.3906/sag-2004-6

Aldrighetti, R., Battini, D., Ivanov, D., & Zennaro, I. (2021). Costs of resilience and disruptions in supply chain network design models: A review and future research directions. *International Journal of Production Economics, 235*(March), 108103. https://doi.org/10.1016/j.ijpe.2021.108103

Aldrighetti, R., Zennaro, I., Finco, S., & Battini, D. (2019). Healthcare supply chain simulation with disruption considerations: A case study from Northern Italy. *Global Journal of Flexible Systems Management, 20*, 81–102. https://doi.org/10.1007/s40171-019-00223-8

Alix, T., Benama, Y., & Perry, N. (2019). A framework for the design of a reconfigurable and mobile manufacturing system. *Procedia Manufacturing, 35*, 304–309. https://doi.org/10.1016/j.promfg.2019.05.044

Ang, E., Iancu, D. A., & Swinney, R. (2017). Disruption risk and optimal sourcing in multitier supply networks. *Management Science, 63*(8), 2397–2771. https://doi.org/10.1287/mnsc.2016.2471

Antony, J., James, W. T., Neriamparambil, A. J., Barot, D. D., & Withers, T. (2020). An Australian response to the COVID-19 pandemic and its implications on the practice of neurosurgery. *World Neurosurgery, 139*, e864–e871. https://doi.org/10.1016/j.wneu.2020.05.136

Ardolino, M., Bacchetti, A., & Ivanov, D. (2022). Analysis of the COVID-19 pandemic's impacts on manufacturing: A systematic literature review and future research agenda. *Operations Management Research*. https://doi.org/10.1007/s12063-021-00225-9

Bier, T., Lange, A., & Glock, C. H. (2020). Methods for mitigating disruptions in complex supply chain structures: A systematic literature review. *International Journal of Production Research, 58*(6), 1835–1856. https://doi.org/10.1080/00207543.2019.1687954

Blackhurst, J., Rungtusanatham, M. J., Scheibe, K., & Ambulkar, S. (2018). Supply chain vulnerability assessment: A network based visualization and clustering analysis approach. *Journal of Purchasing and Supply Management, 24*(1), 21–30. https://doi.org/10.1016/j.pursup.2017.10.004

Cai, M., & Luo, J. (2020). Influence of COVID-19 on manufacturing industry and corresponding countermeasures from supply chain perspective. *Journal of Shanghai Jiaotong University (Science), 24*, 409–416. https://doi.org/10.1007/s12204-020-2206-z

Chowdhury, M. T., Sarkar, A., Paul, S. K., & Moktadir, M. A. (2020). A case study on strategies to deal with the impacts of COVID-19 pandemic in the food and beverage industry. *Operations Management Research*. https://doi.org/10.1007/s12063-020-00166-9

Chowdhury, P., Kumar Paul, S., Kaisar, S., & Abdul Moktadir, M. (2021). COVID-19 pandemic related supply chain studies: A systematic review. *Transportation Research Part E: Logistics and Transportation Review, 148*, 102271. https://doi.org/10.1016/j.tre.2021.102271

Dolgui, A., & Ivanov, D. (2020). Exploring supply chain structural dynamics: New disruptive technologies and disruption risks. *International Journal of Production Economics, 229*, 107886. https://doi.org/10.1016/j.ijpe.2020.107886

Dolgui, A., & Ivanov, D. (2021). Ripple effect and supply chain disruption management: New trends and research directions. *International Journal of Production Research, 59*(1), 102–109. https://doi.org/10.1080/00207543.2021.1840148

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. https://doi.org/10.1080/00207543.2017.1387680

Dolgui, A., Ivanov, D., & Sokolov, B. (2020). Reconfigurable supply chain: The X-network. *In International Journal of Production Research, 58*(13), 4138–4163. https://doi.org/10.1080/00207543.2020.1774679

Durach, C. F., Blesik, T., von Düring, M., & Bick, M. (2021). Blockchain applications in supply chain transactions. *Journal of Business Logistics, 42*(1), 7–24. https://doi.org/10.1111/jbl.12238

Dwivedi, Y. K., Hughes, L., Ismagilova, E., Aarts, G., Coombs, C., Crick, T., Duan, Y., Dwivedi, R., Edwards, J., Eirug, A., Galanos, V., Ilavarasan, P. V., Janssen, M., Jones, P., Kar, A. K., Kizgin, H., Kronemann, B., Lal, B., Lucini, B., ... Williams, M. D. (2019). Artificial Intelligence (AI): Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *International Journal of Information Management, 57*, 101994. https://doi.org/10.1016/j.ijinfomgt.2019.08.002

Fazli-Khalaf, M., Naderi, B., Mohammadi, M., & Pishvaee, M. S. (2020). The design of a resilient and sustainable maximal covering closed-loop supply chain network under hybrid uncertainties: A case study in tire industry. *Environment, Development and Sustainability, 23*, 9949–9973. https://doi.org/10.1007/s10668-020-01041-0

Fernandes, N. (2020). Economic effects of coronavirus outbreak (COVID-19) on the world economy. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3557504
Fornaro, L., & Wolf, M. (2020). *Covid-19 coronavirus and macroeconomic policy: Some analytical notes*. Barcelona GSE Working Paper Series.
Ghosh, D., & Shah, J. (2015). Supply chain analysis under green sensitive consumer demand and cost sharing contract. *International Journal of Production Economics, 164*, 319–329. https://doi.org/10.1016/j.ijpe.2014.11.005
Govindan, K., Mina, H., & Alavi, B. (2020). A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19). *Transportation Research Part E: Logistics and Transportation Review, 138*, 101967. https://doi.org/10.1016/j.tre.2020.101967
Guan, D., Wang, D., Hallegatte, S., Davis, S. J., Huo, J., Li, S., Bai, Y., Lei, T., Xue, Q., Coffman, D. M., Cheng, D., Chen, P., Liang, X., Xu, B., Lu, X., Wang, S., Hubacek, K., & Gong, P. (2020). Global supply-chain effects of COVID-19 control measures. *Nature Human Behaviour, 4*, 577–587. https://doi.org/10.1038/s41562-020-0896-8
Gunasekaran, A., Subramanian, N., & Rahman, S. (2015). Green supply chain collaboration and incentives: Current trends and future directions. *Transportation Research Part E: Logistics and Transportation Review, 74*, 1–10. https://doi.org/10.1016/j.tre.2015.01.002
Hasani, A., & Khosrojerdi, A. (2016). Robust global supply chain network design under disruption and uncertainty considering resilience strategies: A parallel memetic algorithm for a real-life case study. *Transportation Research Part E: Logistics and Transportation Review, 87*, 20–52. https://doi.org/10.1016/j.tre.2015.12.009
Hsu, C., Choon Tan, K., Hanim Mohamad Zailani, S., & Jayaraman, V. (2013). Supply chain drivers that foster the development of green initiatives in an emerging economy. *International Journal of Operations & Production Management, 33*(6), 656–688. https://doi.org/10.1108/IJOPM-10-2011-0401
Ishfaq, R., Davis-Sramek, E., & Gibson, B. (2021). Digital supply chains in omnichannel retail: A conceptual framework. *Journal of Business Logistics, November*, 1–20. https://doi.org/10.1111/jbl.12277
Ivanov, D. (2017). 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). https://doi.org/10.1504/IJISM.2017.083005
Ivanov, D. (2019). Disruption tails and revival policies: A simulation analysis of supply chain design and production-ordering systems in the recovery and post-disruption periods. *Computers and Industrial Engineering, 127*, 558–570. https://doi.org/10.1016/j.cie.2018.10.043
Ivanov, D. (2020a). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research Part E: Logistics and Transportation Review, 136*, 101922. https://doi.org/10.1016/j.tre.2020.101922
Ivanov, D. (2020b). Viable supply chain model: Integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the COVID-19 pandemic. *Annals of Operations Research.*https://doi.org/10.1007/s10479-020-03640-6
Ivanov, D. (2021a). Lean resilience: AURA (Active Usage of Resilience Assets) framework for post-COVID-19 supply chain management. *International Journal of Logistics Management, February.*https://doi.org/10.1108/IJLM-11-2020-0448
Ivanov, D. (2021b). Supply Chain Viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. *International Journal of Production Research, 59*(12), 3535–3552. https://doi.org/10.1080/00207543.2021.1890852
Ivanov, D., & Das, A. (2020). Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: A research note. *International Journal of Integrated Supply Management, 13*(1). https://doi.org/10.1504/IJISM.2020.107780
Ivanov, D., & Dolgui, A. (2021). OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: Managerial insights and research implications. *International Journal of Production Economics, 232*(August), 107921. https://doi.org/10.1016/j.ijpe.2020.107921

Ivanov, D., & Sokolov, B. (2010). Adaptive supply chain management. *Adaptive Supply Chain Management*. https://doi.org/10.1007/978-1-84882-952-7

Ivanov, D., & Sokolov, B. (2013). 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. https://doi.org/10.1016/j.ejor.2012.08.021

Ivanov, D., & Sokolov, B. (2019). Simultaneous structural–operational control of supply chain dynamics and resilience. *Annals of Operations Research, 283*(1–2), 1191–1210. https://doi.org/10.1007/s10479-019-03231-0

Kamalahmadi, M., & Parast, M. M. (2017). An assessment of supply chain disruption mitigation strategies. *International Journal of Production Economics, 184*, 210–230. https://doi.org/10.1016/j.ijpe.2016.12.011

Li, Y., Chen, K., Collignon, S., & Ivanov, D. (2020). Ripple effect in the supply chain network: Forward and backward disruption propagation, network health and firm vulnerability. *European Journal of Operational Research, 291*(2), 1117–1131. https://doi.org/10.1016/j.ejor.2020.09.053

Li, Y., & Zobel, C. W. (2020). Exploring supply chain network resilience in the presence of the ripple effect. *International Journal of Production Economics, 228*, 107693. https://doi.org/10.1016/j.ijpe.2020.107693

Luthra, S., Kumar, V., Kumar, S., & Haleem, A. (2011). Barriers to implement green supply chain management in automobile industry using interpretive structural modeling technique–An Indian perspective. *Journal of Industrial Engineering and Management, 4*(2), 231–257. https://doi.org/10.3926/jiem.2011.v4n2.p231-257

Manuj, I., Esper, T. L., & Stank, T. P. (2014). Supply chain risk management approaches under different conditions of risk. *Journal of Business Logistics, 35*(3), 241–258. https://doi.org/10.1111/jbl.12051

Mehrotra, S., Rahimian, H., Barah, M., Luo, F., & Schantz, K. (2020). A model of supply-chain decisions for resource sharing with an application to ventilator allocation to combat COVID-19. *Naval Research Logistics, 67*(5), 303–320. https://doi.org/10.1002/nav.21905

Munir, M., Jajja, M. S. S., Chatha, K. A., & Farooq, S. (2020). Supply chain risk management and operational performance: The enabling role of supply chain integration. *International Journal of Production Economics, 227*, 107667. https://doi.org/10.1016/j.ijpe.2020.107667

Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-Jabir, A., Iosifidis, C., Agha, M., & Agha, R. (2020). The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *International Journal of Surgery, 78*, 185–193. https://doi.org/10.1016/j.ijsu.2020.04.018

Ortega-Jimenez, C. H., Garrido-Vega, P., & Cruz Torres, C. A. (2020). Achieving plant responsiveness from reconfigurable technology: Intervening role of SCM. *International Journal of Production Economics, 219*, 195–203. https://doi.org/10.1016/j.ijpe.2019.06.001

Papadopoulos, T., Gunasekaran, A., Dubey, R., Altay, N., Childe, S. J., & Fosso-Wamba, S. (2017). The role of Big Data in explaining disaster resilience in supply chains for sustainability. *Journal of Cleaner Production, 142*(2), 1108–1118. https://doi.org/10.1016/j.jclepro.2016.03.059

Paul, S. K., & Chowdhury, P. (2020a). A production recovery plan in manufacturing supply chains for a high-demand item during COVID-19. *International Journal of Physical Distribution and Logistics Management, 51*(2), 104–125. https://doi.org/10.1108/IJPDLM-04-2020-0127

Paul, S. K., & Chowdhury, P. (2020b). Strategies for managing the impacts of disruptions during COVID-19: An example of toilet paper. *Global Journal of Flexible Systems Management, 21*, 283–293. https://doi.org/10.1007/s40171-020-00248-4

Paul, S. K., Sarker, R., & Essam, D. (2017). A quantitative model for disruption mitigation in a supply chain. *European Journal of Operational Research, 257*(3), 881–895. https://doi.org/10.1016/j.ejor.2016.08.035

Pavlov, A., Ivanov, D., Werner, F., Dolgui, A., & Sokolov, B. (2019). Integrated detection of disruption scenarios, the ripple effect dispersal and recovery paths in supply chains. *Annals of Operations Research*. https://doi.org/10.1007/s10479-019-03454-1

Paul, S. K., Chowdhury, P., Chakrabortty, R. K., Ivanov, D., & Sallam, K. (2022). A mathematical model for managing the multi-dimensional impacts of the COVID-19 pandemic in supply chain of a high-demand item. *Annals of Operations Research*. https://doi.org/10.1007/s10479-022-04650-2

Pettit, T. J., Croxton, K. L., & Fiksel, J. (2019). The evolution of resilience in supply chain management: A retrospective on ensuring supply chain resilience. *Journal of Business Logistics, 40*(1), 56–65. https://doi.org/10.1111/jbl.12202

Pivnenko, K., Eriksen, M. K., Martín-Fernández, J. A., Eriksson, E., & Astrup, T. F. (2016). Recycling of plastic waste: Presence of phthalates in plastics from households and industry. *Waste Management, 54*, 44–52. https://doi.org/10.1016/j.wasman.2016.05.014

Poudel, P. B., Poudel, M. R., Gautam, A., Phuyal, S., & Tiwari, C. K. (2020). COVID-19 and its global impact on food and agriculture. *The Journal of Biology and Today's World*. https://doi.org/10.35248/2322-3308.20.09.221

Priya Datta, P., Christopher, M., & Allen, P. (2007). Agent-based modelling of complex production/distribution systems to improve resilience. *International Journal of Logistics Research and Applications, 10*(3), 187–203. https://doi.org/10.1080/13675560701467144

Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso Wamba, S. (2020). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03685-7

Rahman, T., Taghikhah, F., Paul, S. K., Shukla, N., & Agarwal, R. (2021). An agent-based model for supply chain recovery in the wake of the COVID-19 pandemic. *Computers & Industrial Engineering, 158*, 107401. https://doi.org/10.1016/j.cie.2021.107401

Remko, H. (2020). Research opportunities for a more resilient post-COVID-19 supply chain – closing the gap between research findings and industry practice. *International Journal of Operations and Production Management, 40*(4), 341–355. https://doi.org/10.1108/IJOPM-03-2020-0165

Sabouhi, F., Pishvaee, M. S., & Jabalameli, M. S. (2018). Resilient supply chain design under operational and disruption risks considering quantity discount: A case study of pharmaceutical supply chain. *Computers and Industrial Engineering, 126*, 657–672. https://doi.org/10.1016/j.cie.2018.10.001

Sarmah, P. (2020). Global economic impact of COVID 19, with particular reference to India. *International Journal of Advanced Science and Technology*.

Shahed, K. S., Azeem, A., Ali, S. M., & Moktadir, M. A. (2021). A supply chain disruption risk mitigation model to manage COVID-19 pandemic risk. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-020-12289-4

Sharma, M., Luthra, S., Joshi, S., & Kumar, A. (2020). Developing a framework for enhancing survivability of sustainable supply chains during and post-COVID-19 pandemic. *International Journal of Logistics Research and Applications*. https://doi.org/10.1080/13675567.2020.1810213

Singh, R. K., Modgil, S., & Acharya, P. (2019). Assessment of supply chain flexibility using system dynamics modeling. *Global Journal of Flexible Systems Management, 20*, 39–63. https://doi.org/10.1007/s40171-019-00224-7

Song, P., & Karako, T. (2020). COVID-19: Real-time dissemination of scientific information to fight a public health emergency of international concern. *BioScience Trends, 14*(*1*), 1–2. https://doi.org/10.5582/BST.2020.01056

Soren, A., & Shastri, Y. (2019). Resilient design of biomass to energy system considering uncertainty in biomass supply. *Computers and Chemical Engineering, 131*, 106593. https://doi.org/10.1016/j.compchemeng.2019.106593

Taqi, H. M. M., Ahmed, H. N., Paul, S., Garshasbi, M., Ali, S. M., Kabir, G., & Paul, S. K. (2020). Strategies to manage the impacts of the COVID-19 pandemic in the supply chain: Implications for improving economic and social sustainability. *Sustainability (Switzerland), 12*(22), 9483. https://doi.org/10.3390/su12229483

Tarafdar, M., & Qrunfleh, S. (2017). Agile supply chain strategy and supply chain performance: Complementary roles of supply chain practices and information systems capability for agility. *International Journal of Production Research, 55*(4), 925–938. https://doi.org/10.1080/00207543.2016.1203079

Vilarinho, F., Sanches Silva, A., Vaz, M. F., & Farinha, J. P. (2018). Nanocellulose in green food packaging. *Critical Reviews in Food Science and Nutrition, 58*(9), 1526–1537. https://doi.org/10.1080/10408398.2016.1270254

Wu, H.-L., Huang, J., Zhang, C. J. P., He, Z., & Ming, W. K. (2020). Facemask shortage and the novel coronavirus disease (COVID-19) outbreak: Reflections on public health measures. *EClinicalMedicine, 21*, 100329. https://doi.org/10.1016/j.eclinm.2020.100329

Xu, S., Zhang, X., Feng, L., & Yang, W. (2020a). Disruption risks in supply chain management: A literature review based on bibliometric analysis. *International Journal of Production Research, 58*(11), 3508–3526. https://doi.org/10.1080/00207543.2020.1717011

Xu, Z., Elomri, A., Kerbache, L., & El Omri, A. (2020b). Impacts of COVID-19 on global supply chains: Facts and perspectives. *IEEE Engineering Management Review, 48*(3), 153–166. https://doi.org/10.1109/EMR.2020.3018420

Yaya, S., Yaya, S., Otu, A., Otu, A., & Labonté, R. (2020). Globalisation in the time of COVID-19: Repositioning Africa to meet the immediate and remote challenges. *Globalization and Health*. https://doi.org/10.1186/s12992-020-00581-4

Zainal Abidin, N. A., & Ingirige, B. (2018). The dynamics of vulnerabilities and capabilities in improving resilience within Malaysian construction supply chain. *Construction Innovation, 18*(4), 412–432. https://doi.org/10.1108/CI-09-2017-0079

Zhu, G., Chou, M. C., & Tsai, C. W. (2020). Lessons learned from the COVID-19 pandemic exposing the shortcomings of current supply chain operations: A long-term prescriptive offering. *Sustainability (Switzerland), 12*(14), 5858. https://doi.org/10.3390/su12145858

Chapter 6
Impact of Additive Manufacturing on Supply Chain Resilience During COVID-19 Pandemic

Mirco Peron, Fabio Sgarbossa, Dmitry Ivanov, and Alexandre Dolgui

Abstract The use of Additive Manufacturing (AM) has become more widespread in recent years, covering different sectors. The increased interest in AM is due to the main benefits associated with its use, such as the possibility to produce even complex parts on demand and on the service site. These benefits have recently made researchers and practitioners hypothesize that AM can guarantee supply chain (SC) resilience, hence triggering their interest in AM as an emergency solution for SC disruptions. With the COVID-19 pandemic outbreak, this hypothesis has been confirmed to be true. In fact, AM has been shown to be very effective in guaranteeing the restoration and reconstruction of the SC, especially in the production of medical equipment (e.g., face masks, valves for respirators, etc.). However, to the best of the authors' knowledge, the impact of AM on SC resilience has never been quantified before. Similarly, the potentialities of AM to guarantee the resilience of an SC outside of the medical sector have been barely treated (and never in a quantitative way). In this work, we aim to fill these two gaps. To do so, starting from the global supply chain of a company selling lighting equipment (available in the literature), we evaluated the potential of adopting AM as an emergency solution in guaranteeing SC resilience during the COVID-19 pandemic. Specifically, we considered 15 different scenarios where we considered the pandemic outbreak to be limited to the country of production as well as spread worldwide. From the results, the benefits of adopting AM, in terms of revenue, profit, service Level and lead time, were evident. Moreover, from the specific case considered we were also able to draw some general conclusions and suggest to SC managers when the use of AM would be beneficial.

M. Peron (✉) · F. Sgarbossa
Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway
e-mail: mirco.peron@ntnu.no

D. Ivanov
Department of Business and Economics, Berlin School of Economics and Law, Berlin, Germany

A. Dolgui
IMT Atlantique, LS2N-CNRS, La Chantrerie, Nantes cedex 3, France

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_6

Keywords Additive manufacturing · Supply chain resilience · COVID-19

6.1 Introduction

Additive Manufacturing (AM), or 3D printing, is a revolutionary manufacturing process that allows the manufacture of objects directly from a computer-aided design (CAD) model by adding materials layer-by-layer to obtain the desired shapes (Attaran, 2017a). Hence, AM opposes conventional manufacturing (CM) processes that necessitate the subtracting of materials (via machining, milling, carving, etc.) to obtain the desired shapes. In this way, it is possible for AM processes to manufacture complex geometries and customized parts, with lower manufacturing costs. Moreover, in some cases, AM processes also allow the reduction of lead times since parts can be fabricated in a single step, removing the need for assembly. Due to these attractive manufacturing advantages, AM has recently been extensively utilized in the medical, aerospace, and automotive industries (Peron et al., 2018a, 2018b; Rauch et al., 2018; Stavropoulos et al., 2018).

The possibility of producing complex parts in a single step is very attractive, especially for the aerospace and automotive industries, one of the most famous examples being that of GE (Kellner, 2018). In 2018, using AM processes, GE reduced the number of components of a civilian turboprop engine from 855 (with CM) to 12. In this way, GE was able to obtain a reduction in production and assembly costs. But, not only that, the new engine was more than 100 pounds lighter which, in turn, improved the fuel utilization by 20%. Moreover, in the automotive industry, the possibility of producing complex parts in a single step has been used by BMW to directly manufacture hand tools, saving 58% in overall costs and reducing project time by 92% (Giffi et al., 2014). Furthermore, the advantage of part customization is highly utilized in medical applications, where parts can be customized to match the individual patient's data and needs (Javaid and Haleem, 2018). For example, AM is used to manufacture several medical devices such as hip and knee implants, dental braces and stents, and Emelogu et al. (2016) noted that using AM to manufacture such medical devices is always beneficial provided that the cost of these devices in AM is a maximum of three times that of the CM counterparts. Emelogu et al. (2016) reported that the main reason for this strong beneficial impact of AM was the possibility to produce the part on site (i.e., decentralized manufacturing). In fact, the capability of AM to produce small batches in an economic way (AM does not need time- and resource-consuming setups and tooling) allows the deployment of AM machines close to service locations, hence simplifying and reducing the costs of the traditional supply chain (SC). Similarly, the possibility to produce the part on the service site, together with the short production lead times, has also rendered AM interesting for spare part production (Peron and Sgarbossa, 2021; Sgarbossa et al., 2021), especially for spare parts needed in remote locations (Westerweel et al., 2020).

Moreover, this possibility to product parts on the service site, coupled with the possibility to produce them on demand (i.e., whenever a need arises), has rendered it interesting for scenarios where the SC has to be able to cope with unexpected disruption, i.e., the SC has to be resilient. One example of these scenarios is the humanitarian SC, where AM has been adopted to restore and reconstruct stages of humanitarian responses, previously disrupted as a result of disasters due to natural hazards. For example, AM has been used to print umbilical cord clamps in Haiti, overcoming their shortage after the traditional SC from China was disrupted (Saripalle et al., 2016; Corsini et al., 2020). AM has been reported as being able to guarantee the SC resilience, ensuring the proactive and reactive capabilities of the SC (Ivanov et al., 2019). Naghshineh and Carvalho (2020) identified the former as *flexibility*, *integration*, *efficiency*, *redundancy*, *financial strength*, *market strength*, and *disaster readiness*, while the latter as *response* and *recovery capabilities* of firms. AM can improve all of them. For example, Verboeket and Krikke (2019) proposed that AM increases *flexibility*: contrary to CM processes, AM does not require expensive and complicated setups once the machines are in place and running and this enables the setting up of AM machines at almost all points across the SC. Delic et al. (2019) reported that AM adoption has a significant positive influence on SC *integration* since it allows integrated inventory management systems, integrated logistics support systems, and inter-functional data sharing, etc. Zanoni et al. (2019) agreed with Huang et al. (2013) in suggesting that AM can enhance the *efficiency* of an SC as a result of the potential benefits arising from the optimization of the product designs and of the decreased overall inventory level and material movement. According to Attaran (2017b), AM enables the elimination of significant amounts of *redundancy* accumulated in SCs to allow the quick dispatch of parts and products, while, according to Thiesse et al. (2015), local manufacturing can become more *profitable* since AM drastically reduces the benefits of economies of scale attributed to CM processes. Regarding *market strength*, AM can increase it because of the possibility of producing complex parts in a single step. Products with functionally enhanced designs can be dispatched with short lead times, hence increasing the *market strength* (Zanoni et al., 2019). Moreover, the possibility to reduce the lead times increases with market responsiveness (Zanoni et al., 2019). The high *responsiveness* associated with the short lead times positively influences the reactive aspect of SCs since it allows the mitigation of potential disruption in the shortest time and with the least possible impact (Durach et al., 2015; Verboeket and Krikke, 2019). Finally, AM improves *readiness* of an SC by manufacturing service parts on site for remote and/or hard-to-reach locations (e.g., disaster areas) (Meisel et al., 2016). This, in turn, also allows a timely *recovery* from disruptions: the emergency needs can be addressed with notably reduced turn-around times (Meisel et al., 2016).

The capabilities of AM to increase the SC resilience have been (and still are) used during the COVID-19 pandemic, particularly for overcoming the shortage of many protective personal equipment (PPE) (Equbal et al., 2021). For example, to overcome the shortage of valves for respirators, Isinnova (an Italian engineering startup) was able to start the 3D production of these valves in less than 24 h

(ISINNOVA, 2020; Kleinman, 2020; Nazir et al., 2020). Several other examples of the use of AM for overcoming the SC disruptions in the medical sectors can be found (e.g., face masks, face shields, nasopharyngeal swabs, etc.) (Oladapo et al., 2021). However, the COVID-19 pandemic has impacted not only the medical SC but also all the other SCs. According to Ivanov and Dolgui (2020), 94% of the Fortune 1000 companies have been affected by coronavirus-driven SC disruptions, where SCs have experienced either a drastic increase in demand (e.g., facial masks, hand sanitizer, disinfection spray), with the supply not being able to cope with that situation, or a production stop as a consequence of a drastic reduction in the demand (e.g., automotive industry), with an increased risk of bankruptcy and necessity of government support. However, despite the high impact that the COVID-19 pandemic has had on these SCs, to the best of the authors' knowledge only a few studies have investigated the impact of AM on non-medical SCs (Dolgui and Ivanov, 2021; Ivanov and Dolgui, 2020, 2021), and all of them from a qualitative point of view. The aim of this paper is to fill this gap, quantitatively demonstrating how AM can support the SC resilience in non-medical supply chains. To do so, we leverage on the SC described by Ivanov (2020a). Ivanov modeled a global SC of a company selling lighting equipment using anyLogistix and determined the impacts of the COVID-19 pandemic on the SC performance (i.e., revenue, profit, service level). Considering the same supply chain, we also intend to carry out simulations to demonstrate how the SC performance considered by Ivanov (2020a) would have changed if AM had been adopted. To the best of the authors' knowledge, this represents the first work trying to quantify the potentialities of AM with respect to SC resilience, and it might serve as a guideline for practitioners willing to use AM as a manufacturing process to guarantee SC resilience.

The remaining parts of this paper are structured as follows. In Sects. 6.2 and 6.3, a literature analysis on the impacts of AM on the supply chain and on the use of AM in the fight against the COVID-19 pandemic is reported, respectively. Then, Sect. 6.4 deals with the description of the supply chain described by Ivanov (2020a), with the details of the simulation, while Sect. 6.5 deals with the quantification of the impact of AM on the SC performance and discusses the results. Finally, Sect. 6.6 presents the conclusions.

6.2 State of the Art on Impacts of AM on Supply Chain

In this section we summarize the impacts of AM on the SC, highlighting both the benefits and the challenges. Specifically, from the results reported by Kunovjanek et al. (2020), it is possible to understand that AM impacts on two different levels, i.e. the managerial and the operational level. Specifically, the managerial level is involved since AM affects managers' decisions by impacting on the costs and on the environmental sustainability of the supply chain, while the operational level is involved because AM affects the product design, logistics and maintenance.

6.2.1 Impacts of AM on Managerial Level

Laplume et al. (2016) reported that AM can reduce transportation and packaging costs compared to conventional SCs (i.e., SCs where CM processes are used) since it enables the production of parts on the service site (i.e., distributed/decentralized manufacturing approach). The low AM changeover times and setup costs, as well as its digital manufacturing capabilities, in fact, support a demand-driven reallocation of print jobs close to the service location (Weller et al., 2015). However, Chan et al. (2018) argued that the decentralized manufacturing approach will increase licensing and billing costs. Moreover, Westerweel et al. (2018) reported that testing and extensive quality control might represent an additional issue related to the decentralized manufacturing approach. Furthermore, the adoption of a decentralized manufacturing approach is limited by the high investment costs required for AM production capacity and knowledge (Garmulewicz et al., 2018; Martinsuo & Luomaranta, 2018; Thomas, 2016; Weller et al., 2015). Togwe et al. (2019) suggested that one possibility for lowering these costs might be pooling AM capacity across organizations, although this practice would increase organizational effort. Zanoni et al. (2019) and Tosello et al. (2019) then suggested that the high costs related to AM can be balanced by the savings achieved during the utilization phase of the AM products due to the higher functionalities (for example lower product weight achieved via AM results in fuel savings in the aerospace sector).

Ghadge et al. (2018) reported that, due to the short AM production lead times achievable through short cycle times and low setup costs, the use of AM processes allows the reduction of inventory costs. Moreover, Waller and Fawcett (2014) reported that the entire product development process profits from the short cycle times and low setup costs and Thomas (2016) further suggested that the capability of AM to reduce the number of production steps and parties involved, as well as the capability to consolidate different parts in a single complex part, further decreased the costs of the entire product development process. Furthermore, the reduction of the assembly steps related to the consolidation also reduces intermediate part costs such as handling, inventory, and labor costs (Achillas et al., 2015; Weller et al., 2015). In addition, Westerweel et al. (2018) suggested that parts consolidation can also reduce the total lifecycle costs, since it can increase the reliability of AM parts compared to CM counterparts. However, since consolidation renders parts more complex and specific, the total costs might increase. In fact, maintenance operations often become more expensive when parts are consolidated since the entire high-value part has to be replaced, whereas only one cheaper assembly part could have been substituted without consolidation (Knofius et al., 2019).

Furthermore, the literature reported that a major cost benefit that can be gained by using AM processes is that their high raw material efficiency can decrease overall raw material costs (Chiu & Lin, 2016; Gebler et al., 2014; Maccarthy & Ivanov, 2022). For the aerospace industry, for example, the buy-to-fly ratio (i.e., the mass ratio between the input material and the final product) of CM processes typically ranges between 10:1 and 20:1, with peaks of 40:1 for complex components. AM processes offer the advantage of producing near net-shaped products, with the buy-to-fly ratio close to 1:1 (Yusuf et al., 2019). For metal AM, however, raw material costs are still very high and much more expensive than in CM processes, hence they are a significant driver of the total manufacturing costs (Waller & Fawcett, 2014); in some cases, they are even the largest cost factor (Dawes et al., 2015; Scott & Harrison, 2015). Nevertheless, a further cost benefit can arise because AM shifts the customer-order decoupling point upstream in the SC. Because of this, most of the inventory can be kept in the form of raw materials, enabling economies of scale and reducing inventory costs as the raw material can be shared between different products (Thomas, 2016).

It has often been argued that high raw material costs, together the high AM equipment costs, low utilization rates and slow machine throughput times, lead to a lack of economies of scale for AM processes, hence reducing the potential of AM for high production volumes (Baumers et al., 2013; Wagner & Walton, 2016; Weller et al., 2015; Zhang et al., 2017). However, in addition to the shift of the customer-order decoupling point upstream in the SC, other aspects can enable the economies of scale. For example, Li et al. (2017a) reported that it is possible to allocate different orders in one single printing job, hence reducing the costs of the AM parts since the build chamber will be used more efficiently. Moreover, future developments such as printing speed improvements and lower AM investment costs might further render AM processes viable for higher volumes.

The increased raw material efficiency of AM positively affects environmental sustainability (Attaran, 2017a; Bambach et al., 2017; Ben-Ner & Siemsen, 2017; Chiu & Lin, 2016). Additionally, raw materials can also be transported in the form of powder, hence allowing more efficient space utilization and a reduction of carbon emissions (Li et al., 2017b). Moreover, decentralized manufacturing and consolidation further decrease the need for materials (hence the material flows) and the number of SC actors, resulting in a reduction of the environmental impacts (Ford & Despeisse, 2016; Öberg & Shams, 2019). Furthermore, consolidation, together with other design improvements such as weight reduction, improved airflow and thermal efficiency, enhances environmental sustainability during the utilization phase of the final parts (Böckin & Tillman, 2019; Faludi et al., 2015; Ford & Despeisse, 2016; Gebler et al., 2014). Finally, AM reduces the environmental impact because of its recycling possibilities (of both AM waste material and other non-AM wastes). In this way, a reduced requirement for virgin materials and an increased sustainability and energy efficiency of the AM processes can be achieved (Baechler et al., 2013; Garmulewicz et al., 2018; Le et al., 2017; Meisel et al., 2016). By adopting a distributed recycling concept, emissions related to the collection and transportation of wastes can be reduced (Baechler et al., 2013; Chen, 2017; Kreiger et al., 2014).

However, some of the sustainability benefits mentioned above are offset by other aspects. Recycling processing, for example, might be cumbersome sometimes and this, together with the fact that consumers demand high esthetic quality, could rule out the use of recycled materials (Nascimento et al., 2019; Peeters et al., 2019). Furthermore, another limitation to the positive impact of AM on environmental sustainability is the fact that the ecological footprint is increased by the high processing energy requirement for producing both raw materials and final parts (Ingarao et al., 2018; Li et al., 2017b).

6.2.2 *Impact of AM on Operational Level*

AM processes allow the easy production of very complex parts, including complex internal structures, because of the possibility of producing parts layer-by-layer without the need for dedicated tools or molds (Niaki & Nonino, 2017; Peron et al., 2018b; Petrovic et al., 2011; Weller et al., 2015). Because of this design freedom, AM enables optimization of the design of the product according to production constraints and/or goals (Ingarao et al., 2018). For example, the design can be optimized [even iteratively (Fontana et al., 2019)] aiming to minimize and/or maximize specific product characteristics (e.g. product weight) (Zhang et al., 2017; Zhu et al., 2021). Furthermore, separate parts can be consolidated into a single, complex part (Strange & Zucchella, 2017; Waller & Fawcett, 2014; Weller et al., 2015). In this way, products can have a quality even higher than that feasible with CM processes, thus allowing an increased functionality of final parts (Elverum & Welo, 2016). However, to achieve these benefits, skilled and trained operators and designers, and appropriate work structures are required (Oettmeier & Hofmann, 2016; Rylands et al., 2016). These efforts can either be realized internally or outsourced to specialized service providers (Shukla et al., 2018). Furthermore, the use of AM processes is also limited by the fact that the size of the products is limited by the size limitations of the build chamber and by the fact that, often, post-process treatments are required to increase the quality of AM parts (Attaran, 2017a; Livesu et al., 2017; Sgarbossa et al., 2021).

Bogers et al. (2016) then reported that, by using AM, certain creative activities can be shifted from the manufacturer to the consumer, hence strengthening the relationship between customer and manufacturer (Waller & Fawcett, 2014). The online co-creation of products directly between customer and manufacturer is now possible and customer-specific inputs can be accounted for easily (Jia et al., 2016; Oettmeier & Hofmann, 2016). This eliminates intermediate steps in the value chain (Eyers & Potter, 2015; Kothman & Faber, 2016). However, this leads to an increasing number of unique designs and associated legal challenges (Bogers et al., 2016; Weller et al., 2015): for example, Chan et al. (2018) pointed out that customized designs can cause brand dilution or unexpected intellectual property violations. Do (2017) suggested that a possible solution could be software and multi-platform integration, where the exchange of design and manufacturing data to support product design, process planning, production planning, and execution of manufacturing operations is essential. This might be facilitated by a direct integration of e-commerce platforms when dealing with customized designs (Jia et al., 2016), achieved either through block-chain technology to trace the product history

(Mandolla et al., 2019) or through cloud-based solutions that allow simultaneous access to product and process information (Qian et al., 2019).

Since the use of AM allows a decentralized manufacturing approach, where the production of parts can be located close to the service location, even in remote locations, the transportation of finished goods and subcomponents is reduced (Chandima & Ratnayake, 2019; Sasson & Johnson, 2016; Verboeket & Krikke, 2019). AM can improve out-bound logistics by shortening the SC, as well as delivery times and distances, resulting in an increase in on-time deliveries (Hannibal & Knight, 2018; Kleer & Piller, 2019; Muir & Haddud, 2018). Moreover, a further logistical benefit arises due to this localization of production, since customers can approach a local retailer with their needs, and a direct distribution to the customer is possible (Jia et al., 2016). Furthermore, most transportation movements shift upstream in the SC and are handled in the form of raw materials (Ben-Ner & Siemsen, 2017). Such localization, however, means that structural changes are necessary. For example, it is likely that container flows will decrease and that small trucks will be used more frequently (Chen, 2017; Verboeket & Krikke, 2019). Moreover, the increased flexibility and demand variability of these distributed AM networks cause additional complexity for SC planning (Chowdhury et al., 2019). The procurement decisions, for example, are more complex since AM raw materials could be procured from AM equipment suppliers, third party suppliers, or directly from powder atomizers, each of which have different benefits and challenges (Dawes et al., 2015).

Moreover, the possibility of AM to consolidate several parts into a single, complex part allows the reduction of material flow, transportation efforts and related logistical activities (Laplume et al., 2016). Furthermore, the material flow, transportation efforts and related logistical activities can be reduced due to the advantages of AM processes to produce near net-shaped products (i.e., a buy-to-fly ratio close to 1:1) since this reduces raw material consumption during the manufacturing process (Chen, 2017; Gebler et al., 2014; Kothman & Faber, 2016; Yusuf et al., 2019). This potential can be further enhanced through local and flexible material markets that might benefit from localized recycling activities (Despeisse et al., 2017; Garmulewicz et al., 2018) and reduced SC risks (Strange & Zucchella, 2017). One downside, however, is that some AM processes need high-quality resources that are sometimes difficult to transport due to their physical or chemical properties (Meisel et al., 2016).

Finally, maintenance benefits predominantly arise in the context of spare parts production. Printing spare parts on demand and on location reduces inventories and lead times which, in turn, might increase system availability (Eyers & Potter, 2015; Ghadge et al., 2018; Sgarbossa et al., 2021; Verhoef et al., 2018). Moreover, producing spare parts on demand and on location is especially beneficial when penalty costs are high (Li et al., 2019). Furthermore, it reduces downtime and inventory risks by simplifying demand forecasting and planning (Khajavi et al., 2018; Muir & Haddud, 2018). In addition, the downtime and inventory risks, especially the inventory obsolescence, can be reduced by leveraging on virtual spare parts management (Muir & Haddud, 2018). By leveraging on the possibility of producing spare parts on service location, consumers can print their spare parts themselves, to repair previously purchased products (Khajavi et al., 2014). This allows extended product lifecycles (Attaran, 2017a; Eyers & Potter, 2015). Finally, AM has huge potential in the case of legacy systems, in which parts are no longer produced or available on the market (Ballardini et al., 2018). However, one main limitation emerged from the use of AM for spare parts: if parts are consolidated into a single complex part, maintenance operations become more expensive because the entire high-value part now has to be replaced, contrary to unconsolidated parts where only a few, cheaper assembly parts need to be replaced (Knofius et al., 2019).

6.3 AM in the Fight Against COVID-19 Pandemic

Analyzing the global AM response to the COVID-19 pandemic, Kunovjanek and Wankmüller (2020) reported that AM has been vastly used in the fight against COVID-19, with 115 different countries involved. Moreover, they also reported that 90.3% of the AM products manufactured in the fight against COVID-19 can be related to the medical sector. Specifically, the focus of the AM community was to provide the needed PPE. In almost half of all the cases (45.7%), face shields were produced. These face shields are transparent frames that are fixed to a clip attached to either the bearer's head, caps, or even to helmets, and they are used to reduce the fluids exhaled through facial cavities. Throckmorton et al. (2021) reported that from the idea of producing face shields with AM to the realization of the first face shield only took 11 days, confirming the high responsiveness of AM. This short lead time, combined with the fact that many CAD files of face shields are freely available on the internet, renders it intuitive to understand that the production of face shields has been numerous. Kumar and Pumera (2021), for example, reported that Prusa, a well-known AM manufacturer in the Czech Republic, had 3D-printed nearly 200,000 face shields in less than 1 year, in line with what was found by Tareq et al. (2021). Tareq et al. (2021) summarized all of the major efforts put forward to fight COVID-19 through AM, and reported that the production of face shields ranged from 45/day to 500,000/day, depending on the material and number and typology of printers used. Moreover, in agreement with Salmi et al. (2020), Amin et al. (2020) reported that the average cost of 3D-printed face shields is not prohibitive: $7.30, which is not much higher than the price of a traditional face shield.

Kunovjanek and Wankmüller (2020) found that the second most prominent products were parts for ventilators (15.6%), where both component parts (i.e., actual working parts of a ventilator such as venturi valves) and enhancement parts (e.g., airflow splitters that allow the parallel treatment of two or more patients with a single machine) were produced (Longhitano et al., 2021). Ventilators are essential equipment to support patients who are having trouble breathing. During the pandemic, even automobile companies, such as Volkswagen, manufactured AM parts for ventilators (Kumar & Pumera, 2021). At a time when the demand for respirator valves was extremely high and continuously increasing, prompt action taken by Isinnova (an Italian engineering startup) proved to be life-saving. In less than 24 h, Isinnova obtained the design of official venturi valves through reverse-engineering and then manufactured them via AM for a price of almost 1 euro (ISINNOVA, 2020; Kleinman, 2020; Nazir et al., 2020). This method was of huge help to multiple hospitals in Italy, although this prototype could not be widely distributed or used due to copyright issues. Many other companies have now followed INNOVA's example and produced parts for ventilators (e.g. Airflow3D, Weerg, CRP technology, etc.) (CRP Technology, 2020; Editors DE, 2020; Wolf, 2020), and their production was quite substantial, fast and cheap. Patel and Gohil (2020) reported that in 6 months 120,000 ventilator parts were printed via AM by Redington 3D in India alone, and Salmi et al. (2020) reported that the production of ventilator parts, such as venturi valves, ranged from 11/day to 54/day, with a minimum cost of 0.33 €/piece.

The third-largest product group then, according to Kunovjanek and Wankmüller (2020), was facemasks (N95 respirators or N95 masks) (10.7%). The World Health Organization (WHO) recommended that health workers to use N95 respirators to filter particles of bacteria to avoid contamination (Belhouideg, 2020; Livingston et al., 2020). Therefore, N95 respirators were required to be certified prior to use (they have to guarantee a minimum efficiency of 95% for particles larger than 300 nm). Czech Technical University (CTU), collaborating with Czech companies, developed its own N95 prototype, which obtained the CE certification, pledging conformance to EU standard safety requirements. Once the certification was obtained, CTU developed 3D printed molds to mass produce these N95 masks by injection molding (up to 10,000 per day) (Novakova, 2020). Moreover, AM was not only used to build the mold but also to 3D-print the N95 masks. Maker Mask, in fact, designed the first US National Institute of Health (NIH)-approved, 3D printable N95 mask and, using its network, they additively manufactured 100,000 N95 masks from March 2020 to June 2020, for a cost of only $3 per piece (the masks were reusable by only changing the filter). The cost is in line with that reported by Salmi et al. (2020), who also reported that the maximum daily production of a single 3D printer is 80 N95 masks per day, in agreement with what was found by Nazir et al. (2020), who reported a capacity of 60 N95 masks per day.

Mask adjusters (which can reduce the strain on the bearer's ears when wearing regular masks) were reported to be the fourth-largest product group (4.8%) (Kunovjanek & Wankmüller, 2020) but they were mainly produced by hobbyists (Manero et al., 2020).

Nasopharyngeal swabs, used for testing, were another good medical item subjected to severe shortages, and so they were manufactured via AM, representing the fifth larger group (3.8%) (Kunovjanek & Wankmüller, 2020). A nasopharyngeal swab is a flexible stick with a bristle at the end used to collect the COVID-19 testing sample from a patient's nose, and it represents compulsory kit required for the diagnostic testing of a COVID-19 symptomatic person. However, as a result of the exploding demand during the COVID-19 outbreak (Oland et al. (2021) reported that the United States needed from 500 thousand to 30 million swabs per day), there was an unprecedented and high shortage of this kit, especially because, prior to the COVID-19 outbreak, only two companies (Puritan Medical Products, USA and

Copan Diagnostics Inc., Italy) were the top suppliers of such specialized swabs for the entire world (NPR Organisation, 2020). In such a pressing situation, several AM companies collaborated with academia, medical research centers, and hospitals to produce swabs. For example, Beth Israel Deaconess Medical Center (BIDMC), after having obtained four prototypes from the preclinical evaluation of 160 designs and 48 materials of test swabs in just 22 days (Oland et al., 2021), created a consortium with Harvard Medical School and six different certified AM companies to mass produce these swabs; they were able to produce up to 4 million FDA registered test swabs per week (Callahan et al., 2020). Similarly, other consortia have arisen. Formlabs collaborated with three leading US hospitals (i.e., USF Health, Northwell Health, and Tampa General Hospital) to design, develop and test nasopharyngeal swabs to be manufactured via AM (and specifically via Formlabs' 3D printers). Due to an efficient utilization of the build chamber, they were able to produce 300 swabs per each print job, resulting in a production of up to 150,000 swabs per day from all printers (Formlabs, 2020). Similarly, Forecast 3D, in collaboration with Abiogenix, Fathom, and Hewlett-Packard, produced more than 100,000 swabs in 1 day (Tareq et al., 2021). Such high numbers of swabs are producible thanks to the high production rate of each machine, that, according to Salmi et al. (2020), ranges from 780 pcs./day to 2050 pcs./day. Moreover, the cost of each swab ranges from 0.30 to 0.40 € per piece, which is comparable to those obtained with CM.

Other medical products produced to fight the COVID-19 pandemic vary from devices to support virologists during antibody and vaccine research (e.g., bio-printed synthetic lymph nodes) to snorkel mask adapters for ventilation connections, from safety goggles to intubation equipment. More information can be found in (Kumar & Pumera, 2021; Kunovjanek & Wankmüller, 2020; Longhitano et al., 2021; Nazir et al., 2020; Singh et al., 2021; Tareq et al., 2021).

Finally, with respect to the production of non-medical items, hands-free tools (4.8%) were the main produced item. The COVID-19 virus, in fact, may remain on different surfaces for periods of up to 72 h and, therefore, to avoid direct contact with surfaces represents an important way to reduce the chances of contamination (Tino et al., 2020). As a solution for reducing direct hand contact, various hands-free tools (e.g. openers that are fixed to doors) were designed. François et al. (2020) designed and produced a high volume of various hands-free tools to be used in Greater Paris University Hospitals and other sites. Besides hands-free tools, several other, more specialized, initiatives can also be identified. For instance, Winsun (2020), an innovative Chinese construction company, manufactured smart temperature-measuring disinfection checks and isolation homes via AM and these can support hospitals and healthcare operators, especially in densely populated areas.

However, these products are also related to the medical sector and, to the best of the authors' knowledge, any application of AM outside the medical field has been reported in the literature in the fight against the COVID-19 pandemic. Although Ivanov (2020b) and Ivanov (2021) have hypothesized that AM can increase the resilience of industrial supply chains during the COVID-19 pandemic, no quantitative work is available in this respect. The aim of this work is to fill this gap and, in order to do so, we leverage on a simulation study, as will be better described in Sect. 6.4.

6.4 Simulation

To quantitatively demonstrate the potentialities of AM to increase the SC resilience during the COVID-19 pandemic outside of the medical sector, we carried out a simulation in anyLogistix. We adopted the global SC of a company selling lighting equipment, described in Ivanov (2020a), and we used it as benchmark. That study was developed before the worldwide outbreak of the COVID-19 pandemic and Ivanov examined and predicted the impact of the COVID-19 pandemic on the SC performance (i.e., revenue, profit, service level) considering different possible evolutions of the COVID-19 pandemic. In this study, to analyze the impact of AM on the SC resilience, we leveraged on the same pandemic scenarios used by Ivanov and compared the performance of the two SCs, with and without AM. From now on, we will refer to the former as "AM-SC," and to the latter as "CM-SC."

As already mentioned, the CM-SC is a global SC of a company selling lighting equipment, with five different products in total. It is a multi-stage SC with suppliers, factory, distribution centers (DC), and customers located in different geographic zones (Fig. 6.1).

The factories (i.e., the producers) are in China (in Xiamen and Shenzhen) and they are supplied by two local suppliers located very close to the factories (this is why they are not visible in Fig. 6.1). The final products are delivered from the factories to the DCs in the USA, Brazil, and Germany via ship and truck-

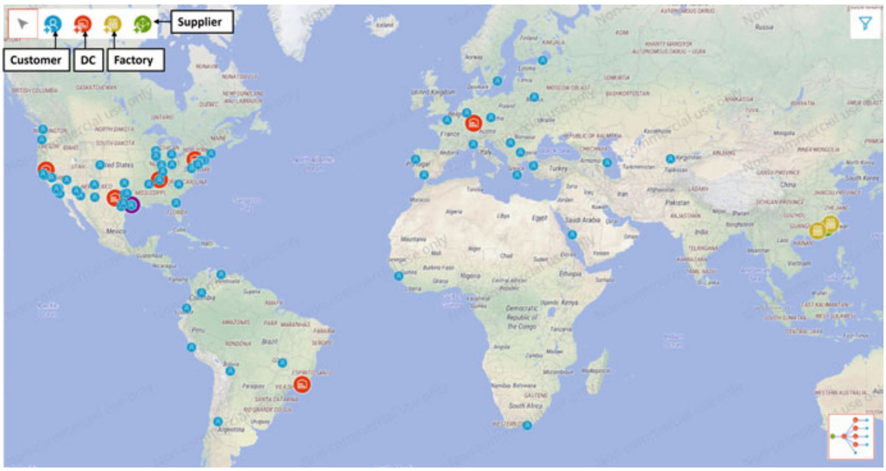


Fig. 6.1 CM-SC design (screenshot from anyLogistix™)

train transportation with an average transportation time of 10 days, then shipped to 95 customers all over the world. It is worth mentioning that, in the USA, the customers are served either directly from the main DC in Houston or via the four regional DCs. The customers order every 5 days (the demand is assumed to be deterministic) with an expected lead-time (ELT) of 7 days. More information about the demand, facilities costs (e.g., inventory holding costs, processing costs, etc.) and other input parameters can be found in the anyLogistix model "SIM Global Network Examination," which is supplied with anyLogistix software and can be seen and run in every anyLogistix version.

The CM-SC considers two main scenarios, one where COVID-19 affects only China (Scenario I), and hence the disruption is limited to there, and one where COVID-19 becomes a pandemic (Scenario II), also affecting the facilities worldwide. COVID-19 is set to close the facilities in China from the 25th of January 2020 and different epidemic durations and different time delays (i.e., the time between the closure of the facilities in China and those worldwide) have also been considered to include different scenarios of epidemic outbreaks, e.g., only in China versus worldwide, simultaneous epidemic crises, and different sequences of opening/closing facilities, for a total of 15 different scenarios. It is worth mentioning that Ivanov (2020a) also considered a third scenario where demand disruption was also included but, in this work, we decided to neglect this scenario since we considered it sufficient for our scope to limit the analysis to the above-mentioned two scenarios. An overview of the different scenarios considered is reported and summarized in Fig. 6.2 and Table 6.1, respectively.

The different scenarios have been considered through a discrete-event simulation methodology and the standard anyLogistix model "SIM Global Network Examination" has been used to solve the simulations. As mentioned before, the parameters used can be found in the anyLogistix model "SIM Global Network Examination,"

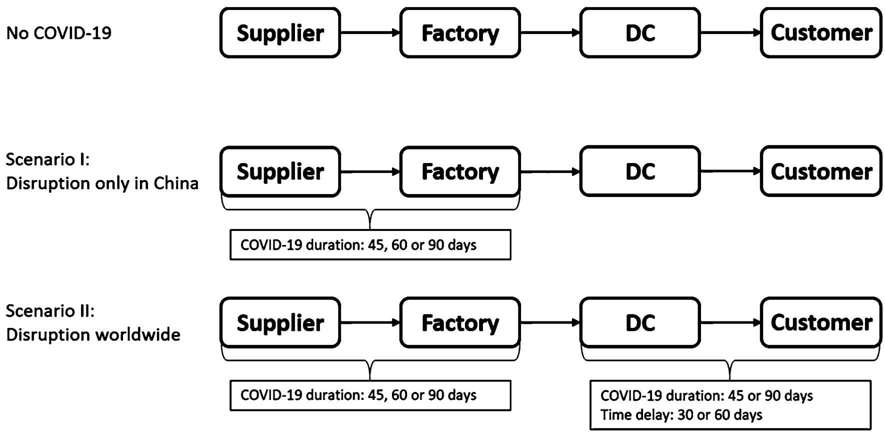


Fig. 6.2 Overview of the different scenarios

Table 6.1 Summary of the different scenarios considered

Scenario	Disruption duration in China (days)	Epidemic delay (days)	Disruption duration worldwide (days)
NO COVID	N/A	N/A	N/A
1a	45	–	–
1b	60	–	–
1c	90	–	–
2a	45	30	45
2b	45	30	90
2c	45	60	45
2d	45	60	90
2e	60	30	45
2f	60	30	90
2g	60	60	45
2h	60	60	90
2i	90	30	45
2j	90	30	90
2k	90	60	45
2l	90	60	90

and the justifications for the use of certain parameters (inventory level, lead times, etc.) can be found in Ivanov (2020a).

Then, to determine the capabilities of AM to increase the SC resilience of the SC under consideration, we developed the AM-SC. In the AM-SC, we considered AM to be activated only as an emergency solution, i.e., only when COVID-19 affects the production in China and/or the distribution worldwide. Specifically, in the latter case, the AM facilities could serve only the customers located in the same country since we assumed the borders to be closed for distribution during a pandemic outbreak. It is worth mentioning that the production times of AM were set three times higher than those of CM. Dealing with the production costs, then, these were also set three times higher than those of CM, based on the work of Knofius et al. (2020), where AM parts were considered to be 1–3 times more expensive than the CM counterparts. In the AM-SC, the production of the AM products was supposed to be outsourced to AM manufacturers and, hence, no initial investments were needed. Moreover, we considered a decentralized scenario, where each DC was served by its own local AM manufacturer, except for the USA, where the DC in Houston is the only one to be served by an AM manufacturer. In this way, we considered a situation as close as possible to the benchmark SC where, among the DCs in the USA, only the DC in Houston was served by the factory in China. It is worth mentioning that, in Fig. 6.3, only the AM manufacturers are visible since their icons cover those of the DCs that are positioned in the same location.

Based on the findings of the work investigating the impact of AM on the fight against COVID-19 in the medical sector (Sect. 6.2.2), approximately 10–25 days are needed to establish the production of AM parts from the conception of the

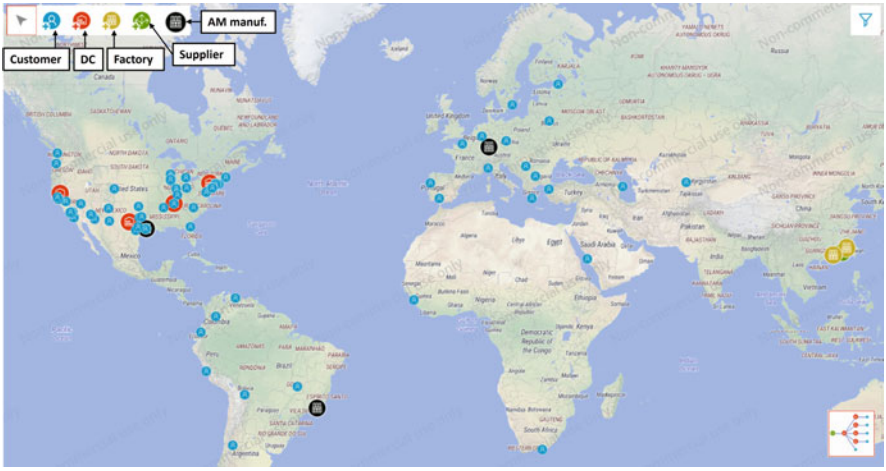


Fig. 6.3 AM-SC design (screenshot from anyLogistix™)

idea. Most of this time is reported to have been spent in obtaining the necessary certifications (e.g., FDA approval); in this study, such certifications are not needed and so we considered the establishment of the AM production to occur 10 days after the closure of the production sites in China. Moreover, as for the CM-SC, when the pandemic outbreaks worldwide and national lockdowns are in place, we consider it possible for the DCs to serve only the customers in the same country.

The results of the CM-SC and AM-SC are reported in the next section, where the results will also be discussed.

6.5 Results and Discussion

To determine the capabilities of AM to increase the SC resilience when a disruption occurs (in this case, the COVID-19 pandemic), we compared the AM-SC with the CM-SC. Specifically, the two SCs have been compared in terms of Revenue, Profit, ELT Service Level and Lead Time, and their results are reported in Table 6.2.

As can be seen from Table 6.2, the adoption of AM in the SC has led to an increased resilience. The AM-SC performed better than the CM-SC in all the disrupted scenarios and with respect to all the performance considered; the revenue, profit, and ELT service level were increased (on average) by 15%, 964%, and 69%, respectively, while the average lead time was reduced by 17%.

The tremendous increase in the achievable profit is highly relevant for the SC. In many disrupted scenarios, in fact, the adoption of AM was able to prevent the negative profits that would have been generated in the CM-SC. This was due to the increased revenues achievable, since the total costs between the two configurations

Table 6.2 Comparison of the CM-SC and AM-SC on the revenue, profit, ELT service level, lead time and total costs

	Revenue (k$)		Profit (k$)		Average ELT service level (%)		Lead time (days)		Total costs (k$)	
Scenario	CM-SC	AM-SC	CM-SC	AM-SC	CM-SC	AM-SC	CM-SC	AM-SC	CM-SC	AM-SC
No COVID	109, 514	–	21, 940	–	1	–	8	–	87,757	–
1a	109, 514	109,514	15, 645	16,869	0.89	0.94	56	43	93,870	92,644
1b	106, 932	109,514	11, 538	16,862	0.65	0.90	83	54	95,637	92,653
1c	103, 261	109,514	3617	16,763	0.34	0.77	110	92	99,799	92,751
2a	101, 829	105,320	7721	14,439	0.60	0.89	88	68	94,108	90,882
2b	84, 054	100,991	−4829	13,096	0.47	0.72	129	115	88,882	87,895
2c	102, 320	105,320	10, 602	14,981	0.62	0.84	92	69	91,718	90,339
2d	89, 460	100,219	1920	13,097	0.47	0.67	166	140	87,540	87,122
2e	101, 829	105,320	7396	14,114	0.60	0.89	88	68	94,433	91,207
2f	84, 054	100,991	−5153	12,771	0.47	0.72	129	115	89,207	88,220
2g	90, 962	105,320	−167	15,085	0.40	0.78	130	99	91,128	90,235
2h	76, 293	99,729	−10, 265	13,417	0.33	0.63	166	163	86,559	86,312
2i	74, 275	105,320	−12, 996	14,070	0.32	0.84	107	90	87,271	91,250
2j	84, 054	100,991	−5619	12,305	0.47	0.72	129	115	89,673	88,685
2k	90, 961	105,320	−632	14,620	0.40	0.78	130	99	91,595	90,700
2l	76, 293	99,729	−10, 731	12,953	0.33	0.63	166	163	87,024	86,776

are comparable (see Table 6.2). By producing closer to the distribution centers, it was still possible to satisfy some of the customer demands, as indicated by the higher service level, despite the epidemic outbreaks in China and/or worldwide and the related imposed limitations on transportation. This highlights the positive implications that reallocating print jobs close to the service location has on the reactive capabilities of the SC, as already suggested by Meisel et al. (2016). In this way, not only is it possible to reduce the lead times, but it is also possible to overcome any transportation-related limitation (Durach et al., 2015; Verboeket & Krikke, 2019). These aspects concur to facilitate the restoration and reconstruction of the SC and have already been discussed by some authors. For example, Ivanov et al. (2019) hypothesized that AM can reduce the SC disruption propagation due to the possibility of producing missing products at the service location. Saripalle et al. (2016) then showed that AM proved to be an effective solution for humanitarian supply chains (they reported the example of the use of AM to overcome the shortage of umbilical cord clamps in Haiti). However, with this work we took a step forward since, for the first time to the best of the authors' knowledge, we were able to quantify the reactive capabilities of the SC when AM is adopted, and the results are impressive. They are even more impressive if we consider that the potentialities of AM have not been exploited thoroughly. In the AM-SC scenario, in fact, we did not modify the structure of the SC, i.e., the production was moved to correspond to the DCs and not the final point of use (i.e., close to the end customers). If we did so, the out-bound logistics would have been improved and the SC shortened, reducing the transportation costs (Chandima & Ratnayake, 2019; Sasson & Johnson, 2016; Verboeket & Krikke, 2019). In this way, the profits would have increased even more compared to the CM-SC solution (now the transportation costs are comparable between CM-SC and AM-SC).

Although these results represent just a first attempt at quantifying the potentialities of AM in terms of improving the SC resilience and are obtained for a specific SC, some general conclusions can still be drawn. Starting from the consideration that a decentralized production will always lead to ELT service levels equal to or greater than those of a centralized production (irrespective of the production method), Li et al. (2019) also suggested that the adoption of AM is the only solution to keep the ELT service level high in case of disruption if the SC is characterized by a centralized production. Therefore, AM needs to be introduced to restore the SC when the main priority of the SC is the ELT Service Level; this might be the case, for example, where high penalties need to be paid if a product is not delivered on time or high backorder costs are encountered if a spare part is missing. Another generalization can be the fact that it is beneficial to introduce AM as an emergency solution when the margins (i.e., the difference between the selling prices and the production costs) are high. In the case herein considered, the selling prices were on average 10 times higher than the production costs in the CM-SC; hence, they could easily absorb the higher production costs of AM products (they were set three times higher than the CM counterparts). However, if the margins are reduced, the introduction of AM might generate more losses. The understanding of the maximum AM overprice that is acceptable is, however, beyond the scope of this work, and it will be studied by the authors in a future work, where more general conclusions will be given.

6.6 Conclusions

In this work, for the first time to the best of the authors' knowledge, we quantified the impact of AM on the SC resilience. Specifically, we focused on a non-medical SC since the impact of AM on the SC resilience of these types of SCs has been overlooked in the literature. Starting from the global SC of a company selling lighting equipment (available in the literature), we developed 15 different disruptive scenarios. More specifically, we considered 15 different possible COVID-19 pandemic outbreaks, considering that the COVID-19 pandemic would have limited its spread only to China or, as it happened, would have spread worldwide. We evaluated the initial SC (i.e., CM-SC) and the SC where the AM was introduced as an emergency solution (i.e., AM-AC) in terms of revenue, profit, ELT service level and lead time, and we found that the adoption of AM led to an improved SC resilience. In fact, the revenue, profit, and ELT service level were increased by 15%, 964%, and 69%, respectively, on average. The lead time was reduced by 17%, on average. We then linked the improved SC resilience of the AM-SC to the possibility provided by AM to easily reallocate the production close to the service location. In this way, it was possible to limit the effects that the imposed local restrictions in transportation and production had on the whole SC. Finally, we generalized the results obtained for the specific SC considered, reporting that AM needs to be introduced as an emergency solution when the main priority of the SC is the ELT service level and when the margins (i.e., the difference between the selling prices and the production costs) are high. In the first case (corresponding to a scenario where high penalties or backorder costs are due when a product is delivered late), the possibility to produce closer to the service location ensures that many more products are delivered on time. In the second case, instead, the high margins can easily absorb the higher production costs of AM products, hence justifying their introduction.

It is worth mentioning that this work represents a first step toward a deep understanding of the impact of AM on SC resilience, and it aimed to provide some preliminary insights into the potentialities of AM. Much still needs to be done to be able to provide more general results and conclusions that might support SC managers in understanding whether or not AM can be beneficial in increasing SC resilience (Ardolino et al., 2022; Ivanov et al., 2022; Dolgui & Ivanov, 2022), and this represents a current topic of research for the authors.

References

Achillas, C., Aidonis, D., Iakovou, E., Thymianidis, M., & Tzetzis, D. (2015). A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. *Journal of Manufacturing Systems, 37*, 328–339. https://doi.org/10.1016/j.jmsy.2014.07.014

Amin, D., Nguyen, N., Roser, S. M., & Abramowicz, S. (2020). 3D printing of face shields during COVID-19 pandemic: A technical note. *Journal of Oral and Maxillofacial Surgery, 78*, 1275–1278. https://doi.org/10.1016/j.joms.2020.04.040

Ardolino, M., Bacchetti, A., & Ivanov, D. (2022). Analysis of the COVID-19 pandemic's impacts on manufacturing: A systematic literature review and future research agenda. *Operations Management Research*. https://doi.org/10.1007/s12063-021-00225-9

Attaran, M. (2017a). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons, 60*, 677–688. https://doi.org/10.1016/j.bushor.2017.05.011

Attaran, M. (2017b). Additive manufacturing: The most promising technology to alter the supply chain and logistics. *Journal of Service Science and Management, 10*, 189–206. https://doi.org/10.4236/jssm.2017.103017

Baechler, C., Devuono, M., & Pearce, J. M. (2013). Distributed recycling of waste polymer into RepRap feedstock. *Rapid Prototyping Journal, 19*, 118–125. https://doi.org/10.1108/13552541311302978

Ballardini, R. M., Flores Ituarte, I., & Pei, E. (2018). Printing spare parts through additive manufacturing: Legal and digital business challenges. *Journal of Manufacturing Technology Management, 29*, 958–982. https://doi.org/10.1108/JMTM-12-2017-0270

Bambach, M., Sviridov, A., Weisheit, A., & Schleifenbaum, J. H. (2017). Case studies on local reinforcement of sheet metal components by laser additive manufacturing. *Metals (Basel), 7*, 113. https://doi.org/10.3390/met7040113

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Rosamond, E., & Hague, R. (2013). Transparency built-in: Energy consumption and cost estimation for additive manufacturing. *Journal of Industrial Ecology, 17*, 418–431. https://doi.org/10.1111/j.1530-9290.2012.00512.x

Belhouideg, S. (2020). Impact of 3D printed medical equipment on the management of the Covid19 pandemic. *International Journal of Health Planning and Management*. https://doi.org/10.1002/hpm.3009

Ben-Ner, A., & Siemsen, E. (2017). Decentralization and localization of production. *California Management Review, 59*, 5–23. https://doi.org/10.1177/0008125617695284

Böckin, D., & Tillman, A. M. (2019). Environmental assessment of additive manufacturing in the automotive industry. *Journal of Cleaner Production, 226*, 977–987. https://doi.org/10.1016/j.jclepro.2019.04.086

Bogers, M., Hadar, R., & Bilberg, A. (2016). Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. *Technological Forecasting and Social Change, 102*, 225–239. https://doi.org/10.1016/j.techfore.2015.07.024

Callahan, C. J., Lee, R., Zulauf, K. E., Tamburello, L., Smith, K. P., Previtera, J., Cheng, A., Green, A., Azim, A. A., Yano, A., Doraiswami, N., Kirby, J. E., & Arnaout, R. A. (2020). Open development and clinical validation of multiple 3D-printed nasopharyngeal collection swabs: Rapid resolution of a critical COVID-19 testing bottleneck. *Journal of Clinical Microbiology, 58*, 876–896. https://doi.org/10.1128/JCM.00876-20

Chan, H. K., Griffin, J., Lim, J. J., Zeng, F., & Chiu, A. S. F. (2018). The impact of 3D Printing Technology on the supply chain: Manufacturing and legal perspectives. *International Journal of Production Economics, 205*, 156–162. https://doi.org/10.1016/j.ijpe.2018.09.009

Chandima Ratnayake, R. M. (2019). Enabling RDM in challenging environments via additive layer manufacturing: Enhancing offshore petroleum asset operations. *Production Planning and Control, 30*, 522–539. https://doi.org/10.1080/09537287.2018.1540054

Chen, Z. (2017). The influence of 3D printing on global container multimodal transport system. *Complexity*. https://doi.org/10.1155/2017/7849670

Chiu, M. C., & Lin, Y. H. (2016). Simulation based method considering design for additive manufacturing and supply chain. An empirical study of lamp industry. *Industrial Management & Data Systems, 116*, 322–348. https://doi.org/10.1108/IMDS-07-2015-0266

Chowdhury, S., Shahvari, O., Marufuzzaman, M., Francis, J., & Bian, L. (2019). Sustainable design of on-demand supply chain network for additive manufacturing. *IISE Transactions, 51*, 744–765. https://doi.org/10.1080/24725854.2018.1532134

Corsini, L., Aranda-Jan, C. B., & Moultrie, J. (2020). The impact of 3D printing on the humanitarian supply chain. *Production Planning and Control*. https://doi.org/10.1080/09537287.2020.1834130

CRP Technology. (2020). *CRP Technology on the front line in the fight against Covid-19* [WWW Document]. Accessed May 29, 2021, from https://www.crptechnology.com/front-line-fight-against-covid19-mask-3d-printing/

Dawes, J., Bowerman, R., & Trepleton, R. (2015). Introduction to the additive manufacturing powder metallurgy supply chain. *Johnson Matthey Technology Review*. https://doi.org/10.1595/205651315X688686

Delic, M., Eyers, D. R., & Mikulic, J. (2019). Additive manufacturing: Empirical evidence for supply chain integration and performance from the automotive industry. *Supply Chain Management, 24*, 604–621. https://doi.org/10.1108/SCM-12-2017-0406

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S., Minshall, T. H. W., Mortara, L., Reed-Tsochas, F. P., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change, 115*, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Do, N. (2017). Integration of design and manufacturing data to support personal manufacturing based on 3D printing services. *International Journal of Advanced Manufacturing Technology, 90*, 3761–3773. https://doi.org/10.1007/s00170-016-9688-8

Dolgui, A., & Ivanov, D. (2021). Ripple effect and supply chain disruption management: New trends and research directions. *International Journal of Production Research, 59*(1), 102–109. https://doi.org/10.1080/00207543.2021.1840148

Dolgui, A., & Ivanov, D. (2022). 5G in digital supply chain and operations management: Fostering flexibility, end-to-end connectivity and real-time visibility through internet-of-everything. *International Journal of Production Research, 60*(2), 442–451.

Durach, C. F., Wieland, A., & Machuca, J. A. D. (2015). Antecedents and dimensions of supply chain robustness: A systematic literature review. *International Journal of Physical Distribution and Logistics Management, 45*, 118–137. https://doi.org/10.1108/IJPDLM-05-2013-0133

Editors DE. (2020). *Weerg 3D prints valves for emergency respiratory masks – digital engineering 24/7* [WWW Document]. Accessed May 29, 2021, from https://www.digitalengineering247.com/article/weerg-3d-prints-valves-for-emergency-respiratory-masks

Elverum, C. W., & Welo, T. (2016). Leveraging prototypes to generate value in the concept-to-production process: A qualitative study of the automotive industry. *International Journal of Production Research, 54*, 3006–3018. https://doi.org/10.1080/00207543.2016.1152406

Emelogu, A., Marufuzzaman, M., Thompson, S. M., Shamsaei, N., & Bian, L. (2016). Additive manufacturing of biomedical implants: A feasibility assessment via supply-chain cost analysis. *Additive Manufacturing, 11*, 97–113. https://doi.org/10.1016/j.addma.2016.04.006

Equbal, A., Akhter, S., Sood, A. K., & Equbal, I. (2021). The usefulness of additive manufacturing (AM) in COVID-19. *Annals of 3D Printed Medicine, 2*, 100013. https://doi.org/10.1016/j.stlm.2021.100013

Eyers, D. R., & Potter, A. T. (2015). E-commerce channels for additive manufacturing: An exploratory study. *Journal of Manufacturing Technology Management, 26*, 390–411. https://doi.org/10.1108/JMTM-08-2013-0102

Faludi, J., Bayley, C., Bhogal, S., & Iribarne, M. (2015). Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal, 21*, 14–33. https://doi.org/10.1108/RPJ-07-2013-0067

Fontana, F., Klahn, C., & Meboldt, M. (2019). Value-driven clustering of industrial additive manufacturing applications. *Journal of Manufacturing Technology Management, 30*, 366–390. https://doi.org/10.1108/JMTM-06-2018-0167

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *Journal of Cleaner Production, 137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Formlabs. (2020). *3D printed COVID-19 test swabs* [WWW Document]. Accessed May 31, 2021, from https://formlabs.com/covid-19-response/covid-test-swabs/

François, P. M., Bonnet, X., Kosior, J., Adam, J., & Khonsari, R. H. (2020). 3D-printed contact-free devices designed and dispatched against the COVID-19 pandemic: The 3D COVID initiative. *Journal of Stomatology Oral and Maxillofacial Surgery*. https://doi.org/10.1016/j.jormas.2020.06.010

Garmulewicz, A., Holweg, M., Veldhuis, H., & Yang, A. (2018). Disruptive technology as an enabler of the circular economy: What potential does 3D printing hold? *California Management Review, 60*, 112–132. https://doi.org/10.1177/0008125617752695

Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy, 74*, 158–167. https://doi.org/10.1016/j.enpol.2014.08.033

Ghadge, A., Karantoni, G., Chaudhuri, A., & Srinivasan, A. (2018). Impact of additive manufacturing on aircraft supply chain performance: A system dynamics approach. *Journal of Manufacturing Technology Management, 29*, 846–865. https://doi.org/10.1108/JMTM-07-2017-0143

Giffi, C. A., Gangula, B., & Illinda, P. (2014). *3D opportunity in the automotive industry. Additive manufacturing hits the road. A Deloitte series on additive manufacturing*. Deloitte University Press.

Hannibal, M., & Knight, G. (2018). Additive manufacturing and the global factory: Disruptive technologies and the location of international business. *International Business Review, 27*, 1116–1127. https://doi.org/10.1016/j.ibusrev.2018.04.003

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: A literature review. *International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-012-4558-5

Ingarao, G., Priarone, P. C., Deng, Y., & Paraskevas, D. (2018). Environmental modelling of aluminium based components manufacturing routes: Additive manufacturing versus machining versus forming. *Journal of Cleaner Production, 176*, 261–275. https://doi.org/10.1016/j.jclepro.2017.12.115

ISINNOVA. (2020). *Charlotte valve – easy Covid-19* [WWW Document]. Accessed May 29, 2021, from https://isinnova.it/archivio-progetti/easy-covid-19/

Ivanov, D. (2020a). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research – Part E: Logistics and Transportation Review, 136*, 101922. https://doi.org/10.1016/j.tre.2020.101922

Ivanov, D. (2020b). Viable supply chain model: Integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the COVID-19 pandemic. *Annals of Operations Research*, 1–21. https://doi.org/10.1007/s10479-020-03640-6

Ivanov, D. (2021). Lean resilience: AURA (Active Usage of Resilience Assets) framework for post-COVID-19 supply chain management. *International Journal of Logistics Management*. https://doi.org/10.1108/IJLM-11-2020-0448

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research, 58*, 2904–2915. https://doi.org/10.1080/00207543.2020.1750727

Ivanov, D., & Dolgui, A. (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning and Control, 32*(9), 775–788. https://doi.org/10.1080/09537287.2020.1768450

Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research, 57*, 829–846. https://doi.org/10.1080/00207543.2018.1488086

Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "supply chain-as-a-service". *Transportation Research – Part E: Logistics and Transportation Review, 160*, 102676.

Javaid, M., & Haleem, A. (2018). Additive manufacturing applications in medical cases: A literature based review. *Alexandria Journal of Medicine, 54*, 411–422. https://doi.org/10.1016/j.ajme.2017.09.003

Jia, F., Wang, X., Mustafee, N., & Hao, L. (2016). Investigating the feasibility of supply chain-centric business models in 3D chocolate printing: A simulation study. *Technological Forecasting and Social Change, 102*, 202–213. https://doi.org/10.1016/j.techfore.2015.07.026

Kellner, T. (2018). *Fired up: GE successfully tested its advanced turboprop engine with 3D-printed parts* | GE News [WWW Document]. Accessed May 31, 2021, from https://www.ge.com/news/reports/ge-fired-its-3d-printed-advanced-turboprop-engine

Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in Industry, 65*, 50–63. https://doi.org/10.1016/j.compind.2013.07.008

Khajavi, S. H., Holmström, J., & Partanen, J. (2018). Additive manufacturing in the spare parts supply chain: Hub configuration and technology maturity. *Rapid Prototyping Journal, 24*, 1178–1192. https://doi.org/10.1108/RPJ-03-2017-0052

Kleer, R., & Piller, F. T. (2019). Local manufacturing and structural shifts in competition: Market dynamics of additive manufacturing. *International Journal of Production Economics, 216*, 23–34. https://doi.org/10.1016/j.ijpe.2019.04.019

Kleinman, Z. (2020). *Coronavirus: 3D printers save hospital with valves* – BBC News [WWW Document]. Accessed May 29, 2021, from https://www.bbc.com/news/technology-51911070

Knofius, N., van der Heijden, M. C., Sleptchenko, A., & Zijm, W. H. M. (2020). Improving effectiveness of spare parts supply by additive manufacturing as dual sourcing option. *OR Spectrum, 43*, 189–221. https://doi.org/10.1007/s00291-020-00608-7

Knofius, N., van der Heijden, M. C., & Zijm, W. H. M. (2019). Consolidating spare parts for asset maintenance with additive manufacturing. *International Journal of Production Economics, 208*, 269–280. https://doi.org/10.1016/j.ijpe.2018.11.007

Kothman, I., & Faber, N. (2016). How 3D printing technology changes the rules of the game Insights from the construction sector. *Journal of Manufacturing Technology Management, 27*, 932–943. https://doi.org/10.1108/JMTM-01-2016-0010

Kreiger, M. A., Mulder, M. L., Glover, A. G., & Pearce, J. M. (2014). Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. *Journal of Cleaner Production, 70*, 90–96. https://doi.org/10.1016/j.jclepro.2014.02.009

Kumar, K. P. A., & Pumera, M. (2021). 3D-printing to mitigate COVID-19 pandemic. *Advanced Functional Materials, 31*, 2100450. https://doi.org/10.1002/adfm.202100450

Kunovjanek, M., Knofius, N., & Reiner, G. (2020). Additive manufacturing and supply chains–a systematic review. *Production Planning and Control*. https://doi.org/10.1080/09537287.2020.1857874

Kunovjanek, M., & Wankmüller, C. (2020). An analysis of the global additive manufacturing response to the COVID-19 pandemic. *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-07-2020-0263

Laplume, A. O., Petersen, B., & Pearce, J. M. (2016). Global value chains from a 3D printing perspective. *Journal of International Business Studies*. https://doi.org/10.1057/jibs.2015.47

Le, V. T., Paris, H., & Mandil, G. (2017). Process planning for combined additive and subtractive manufacturing technologies in a remanufacturing context. *Journal of Manufacturing Systems, 44*, 243–254. https://doi.org/10.1016/j.jmsy.2017.06.003

Li, Q., Kucukkoc, I., & Zhang, D. Z. (2017a). Production planning in additive manufacturing and 3D printing. *Computers and Operations Research, 83*, 1339–1351. https://doi.org/10.1016/j.cor.2017.01.013

Li, Y., Jia, G., Cheng, Y., & Hu, Y. (2017b). Additive manufacturing technology in spare parts supply chain: A comparative study. *International Journal of Production Research, 55*, 1498–1515. https://doi.org/10.1080/00207543.2016.1231433

Li, Y., Cheng, Y., Hu, Q., Zhou, S., Ma, L., & Lim, M. K. (2019). The influence of additive manufacturing on the configuration of make-to-order spare parts supply chain under heterogeneous demand. *International Journal of Production Research, 57*, 3622–3641. https://doi.org/10.1080/00207543.2018.1543975

Livesu, M., Ellero, S., Martínez, J., Lefebvre, S., & Attene, M. (2017). From 3D models to 3D prints: An overview of the processing pipeline. *Computer Graphics Forum, 36*, 537–564. https://doi.org/10.1111/cgf.13147

Livingston, E., Desai, A., & Berkwits, M. (2020). Sourcing personal protective equipment during the COVID-19 pandemic. *JAMA*. https://doi.org/10.1001/jama.2020.5317

Longhitano, G. A., Nunes, G. B., Candido, G., & da Silva, J. V. L. (2021). The role of 3D printing during COVID-19 pandemic: A review. *Progress in Additive Manufacturing*. https://doi.org/10.1007/s40964-020-00159-x

MacCarthy, B., & Ivanov, D. (2022). *Digital supply chain*. Elsevier.

Mandolla, C., Petruzzelli, A. M., Percoco, G., & Urbinati, A. (2019). Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry. *Computers in Industry, 109*, 134–152. https://doi.org/10.1016/j.compind.2019.04.011

Manero, A., Smith, P., Koontz, A., Dombrowski, M., Sparkman, J., Courbin, D., & Chi, A. (2020). Leveraging 3D printing capacity in times of crisis: Recommendations for COVID-19 distributed manufacturing for medical equipment rapid response. *International Journal of Environmental Research and Public Health, 17*, 1–17. https://doi.org/10.3390/ijerph17134634

Martinsuo, M., & Luomaranta, T. (2018). Adopting additive manufacturing in SMEs: Exploring the challenges and solutions. *Journal of Manufacturing Technology Management, 29*, 937–957. https://doi.org/10.1108/JMTM-02-2018-0030

Meisel, N. A., Williams, C. B., Ellis, K. P., & Taylor, D. (2016). Decision support for additive manufacturing deployment in remote or austere environments. *Journal of Manufacturing Technology Management, 27*, 898–914. https://doi.org/10.1108/JMTM-06-2015-0040

Muir, M., & Haddud, A. (2018). Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain. *Journal of Manufacturing Technology Management, 29*, 372–397. https://doi.org/10.1108/JMTM-01-2017-0004

Naghshineh, B., & Carvalho, H. (2020). The impact of additive manufacturing on supply chain resilience. In *IFIP advances in information and communication technology* (pp. 214–221). Springer. https://doi.org/10.1007/978-3-030-45124-0_20

Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Lona, L. R., & Tortorella, G. (2019). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-03-2018-0071

Nazir, A., Azhar, A., Nazir, U., Liu, Y. F., Qureshi, W. S., Chen, J. E., & Alanazi, E. (2020). The rise of 3D Printing entangled with smart computer aided design during COVID-19 era. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2020.10.009

Niaki, M. K., & Nonino, F. (2017). Impact of additive manufacturing on business competitiveness: A multiple case study. *Journal of Manufacturing Technology Management, 28*, 56–74. https://doi.org/10.1108/JMTM-01-2016-0001

Novakova, A. (2020). *Mass production of original Czech mask with the highest degree of protection has been launched. More than thirty Czech companies helped with preparations* | CIIRC [WWW Document]. Accessed May 29, 2021, from https://www.ciirc.cvut.cz/seriova-vyroba-ceske-masky-s-nejvyssim-stupnem-ochrany-byla-zahajena-do-priprav-se-zapojilo-vice-nez-tricet-ceskych-spolecnosti/

NPR Organisation. (2020). *Testing swabs run in short supply as makers try to speed up production* [WWW Document]. Accessed May 31, 2021, from https://www.npr.org/sections/health-shots/2020/03/18/817801222/testing-swabs-run-in-short-supply-as-makers-try-to-speed-up-production

Öberg, C., & Shams, T. (2019). On the verge of disruption: Rethinking position and role – the case of additive manufacturing. *The Journal of Business and Industrial Marketing, 34*, 1093–1105. https://doi.org/10.1108/JBIM-10-2018-0293

Oettmeier, K., & Hofmann, E. (2016). Impact of additive manufacturing technology adoption on supply chain management processes and components. *Journal of Manufacturing Technology Management, 27*, 944–968. https://doi.org/10.1108/JMTM-12-2015-0113

Oladapo, B. I., Ismail, S. O., Afolalu, T. D., Olawade, D. B., & Zahedi, M. (2021). Review on 3D printing: Fight against COVID-19. *Materials Chemistry and Physics, 258*, 123943. https://doi.org/10.1016/j.matchemphys.2020.123943

Oland, G., Garner, O., & de St Maurice, A. (2021). Prospective clinical validation of 3D printed nasopharyngeal swabs for diagnosis of COVID-19. *Diagnostic Microbiology and Infectious Disease, 99*, 115257. https://doi.org/10.1016/j.diagmicrobio.2020.115257

Patel, P., & Gohil, P. (2020). Role of additive manufacturing in medical application COVID-19 scenario: India case study. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2020.11.006

Peeters, B., Kiratli, N., & Semeijn, J. (2019). A barrier analysis for distributed recycling of 3D printing waste: Taking the maker movement perspective. *Journal of Cleaner Production, 241*, 118313. https://doi.org/10.1016/j.jclepro.2019.118313

Peron, M., & Sgarbossa, F. (2021). Additive manufacturing and spare parts: Literature review and future perspectives. In *Lecture Notes in Electrical Engineering* (pp. 629–635). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-981-33-6318-2_78

Peron, M., Torgersen, J., & Berto, F. (2018a). Rupture predictions of notched Ti-6Al-4V using local approaches. *Materials (Basel)., 11*, 663. https://doi.org/10.3390/ma11050663

Peron, M., Torgersen, J., Ferro, P., & Berto, F. (2018b). Fracture behaviour of notched as-built EBM parts: Characterization and interplay between defects and notch strengthening behaviour. *Theoretical and Applied Fracture Mechanics, 98*, 178–185. https://doi.org/10.1016/J.TAFMEC.2018.10.004

Petrovic, V., Vicente Haro Gonzalez, J., Jordá Ferrando, O., Delgado Gordillo, J., Ramon Blasco Puchades, J., & Portoles Grinan, L. (2011). Additive layered manufacturing: Sectors of industrial application shown through case studies. *International Journal of Production Research, 49*, 1061–1079. https://doi.org/10.1080/00207540903479786

Qian, C., Zhang, Y., Liu, Y., & Wang, Z. (2019). A cloud service platform integrating additive and subtractive manufacturing with high resource efficiency. *Journal of Cleaner Production, 241*, 118379. https://doi.org/10.1016/j.jclepro.2019.118379

Rauch, E., Unterhofer, M., & Dallasega, P. (2018). Industry sector analysis for the application of additive manufacturing in smart and distributed manufacturing systems. *Manufacturing Letters, 15*, 126–131. https://doi.org/10.1016/j.mfglet.2017.12.011

Rylands, B., Böhme, T., Gorkin, R., Fan, J., & Birtchnell, T. (2016). The adoption process and impact of additive manufacturing on manufacturing systems. *Journal of Manufacturing Technology Management, 27*, 969–989. https://doi.org/10.1108/JMTM-12-2015-0117

Salmi, M., Akmal, J. S., Pei, E., Wolff, J., Jaribion, A., & Khajavi, S. H. (2020). 3D printing in COVID-19: Productivity estimation of the most promising open source solutions in emergency situations. *Applied Sciences, 10*, 4004. https://doi.org/10.3390/app10114004

Saripalle, S., Maker, H., Bush, A., & Lundman, N. (2016). 3D printing for disaster preparedness: Making life-saving supplies on-site, on-demand, on-time. In *GHTC 2016 – IEEE Global Humanitarian Technology Conference: Technology for the Benefit of Humanity, Conference Proceedings* (pp. 205–208). Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/GHTC.2016.7857281

Sasson, A., & Johnson, J. C. (2016). The 3D printing order: Variability, supercenters and supply chain reconfigurations. *International Journal of Physical Distribution and Logistics Management, 46*, 82–94. https://doi.org/10.1108/IJPDLM-10-2015-0257

Scott, A., & Harrison, T. P. (2015). Additive manufacturing in an end-to-end supply chain setting. *3D Printing or Additive Manufacturing, 2*, 65–77. https://doi.org/10.1089/3dp.2015.0005

Sgarbossa, F., Peron, M., Lolli, F., & Balugani, E. (2021). Conventional or additive manufacturing for spare parts management: An extensive comparison for Poisson demand. *International Journal of Production Economics, 233*, 107993. https://doi.org/10.1016/j.ijpe.2020.107993

Shukla, M., Todorov, I., & Kapletia, D. (2018). Application of additive manufacturing for mass customisation: Understanding the interaction of critical barriers. *Production Planning and Control, 29*, 814–825. https://doi.org/10.1080/09537287.2018.1474395

Singh, S. N., Venkatesh, V. S. S., & Deoghare, A. B. (2021). A review on the role of 3D printing in the fight against COVID-19: Safety and challenges. *Rapid Prototyping Journal*. https://doi.org/10.1108/RPJ-08-2020-0198

Stavropoulos, P., Foteinopoulos, P., Papacharalampopoulos, A., & Bikas, H. (2018). Addressing the challenges for the industrial application of additive manufacturing: Towards a hybrid solution. *International Journal of Lightweight Materials and Manufacture, 1*, 157–168. https://doi.org/10.1016/j.ijlmm.2018.07.002

Strange, R., & Zucchella, A. (2017). Industry 4.0, global value chains and international business. *Multinational Business Review, 25*, 174–184. https://doi.org/10.1108/MBR-05-2017-0028

Tareq, M. S., Rahman, T., Hossain, M., & Dorrington, P. (2021). Additive manufacturing and the COVID-19 challenges: An in-depth study. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2020.12.021

Thiesse, F., Wirth, M., Kemper, H. G., Moisa, M., Morar, D., Lasi, H., Piller, F., Buxmann, P., Mortara, L., Ford, S., & Minshall, T. (2015). Economic implications of additive manufacturing and the contribution of MIS. *Business & Information Systems Engineering*. https://doi.org/10.1007/s12599-015-0374-4

Thomas, D. (2016). Costs, benefits, and adoption of additive manufacturing: A supply chain perspective. *International Journal of Advanced Manufacturing Technology, 85*, 1857–1876. https://doi.org/10.1007/s00170-015-7973-6

Throckmorton, A. L., Bass, E. J., Ferrick, B., Ramakrishnan, A., Eichmann, S., Catucci, N., Eshelman, B., McNamara, J., Sundquist, E., Beatson, N., Hirschhorn, M., Menon, P., Datner, E., Stevens, R., & Marcolongo, M. (2021). A cross university-led COVID-19 rapid-response effort: Design, build, and distribute Drexel AJFlex face shields. *Annals of Biomedical Engineering*. https://doi.org/10.1007/s10439-021-02743-w

Tino, R., Moore, R., Antoline, S., Ravi, P., Wake, N., Ionita, C. N., Morris, J. M., Decker, S. J., Sheikh, A., Rybicki, F. J., & Chepelev, L. L. (2020). COVID-19 and the role of 3D printing in medicine. *3D Printing in Medicine, 6*, 1–8. https://doi.org/10.1186/s41205-020-00064-7

Togwe, T., Eveleigh, T. J., & Tanju, B. (2019). An additive manufacturing spare parts inventory model for an aviation use case. *Engineering Management Journal, 31*, 69–80. https://doi.org/10.1080/10429247.2019.1565618

Tosello, G., Charalambis, A., Kerbache, L., Mischkot, M., Pedersen, D. B., Calaon, M., & Hansen, H. N. (2019). Value chain and production cost optimization by integrating additive manufacturing in injection molding process chain. *International Journal of Advanced Manufacturing Technology, 100*, 783–795. https://doi.org/10.1007/s00170-018-2762-7

Verboeket, V., & Krikke, H. (2019). The disruptive impact of additive manufacturing on supply chains: A literature study, conceptual framework and research agenda. *Computers in Industry, 111*, 91–107. https://doi.org/10.1016/j.compind.2019.07.003

Verhoef, L. A., Budde, B. W., Chockalingam, C., García Nodar, B., & van Wijk, A. J. M. (2018). The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach. *Energy Policy, 112*, 349–360. https://doi.org/10.1016/j.enpol.2017.10.034

Wagner, S. M., & Walton, R. O. (2016). Additive manufacturing's impact and future in the aviation industry. *Production Planning and Control, 27*, 1124–1130. https://doi.org/10.1080/09537287.2016.1199824

Waller, M. A., & Fawcett, S. E. (2014). Click here to print a maker movement supply chain: How invention and entrepreneurship will disrupt supply chain design. *Journal of Business Logistics*. https://doi.org/10.1111/jbl.12045

Weller, C., Kleer, R., & Piller, F. T. (2015). Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. *International Journal of Production Economics, 164*, 43–56. https://doi.org/10.1016/j.ijpe.2015.02.020

Westerweel, B., Basten, R., den Boer, J., & van Houtum, G. (2020). Printing spare parts at remote locations: Fulfilling the promise of additive manufacturing. *Production and Operations Management, 30*, 1615–1632. https://doi.org/10.1111/poms.13298

Westerweel, B., Basten, R. J. I., & van Houtum, G. J. (2018). Traditional or additive manufacturing? Assessing component design options through lifecycle cost analysis. *European Journal of Operational Research, 270*, 570–585. https://doi.org/10.1016/j.ejor.2018.04.015

Winsun. (2020). *WINSUN makes global donation of 3D printed isolation houses* [WWW Document]. Accessed May 31, 2021, from http://www.winsun3d.com/En/News/news_inner/id/547

Wolf, E. (2020). *AIRWOLF3D offering emergency additive manufacturing services* | Airwolf 3D [WWW Document]. Accessed May 29, 2021, from https://airwolf3d.com/2020/03/17/airwolf3d-offering-emergency-additive-manufacturing-services/

Yusuf, S. M., Cutler, S., & Gao, N. (2019). Review: The impact of metal additive manufacturing on the aerospace industry. *Metals (Basel)*. https://doi.org/10.3390/met9121286

Zanoni, S., Ashourpour, M., Bacchetti, A., Zanardini, M., & Perona, M. (2019). Supply chain implications of additive manufacturing: A holistic synopsis through a collection of case studies. *International Journal of Advanced Manufacturing Technology, 102*, 3325–3340. https://doi.org/10.1007/s00170-019-03430-w

Zhang, J. L., Zhang, Z., & Han, Y. (2017). Research on manufacturability optimization of discrete products with 3D printing involved and lot-size considered. *Journal of Manufacturing Systems, 43*, 150–159. https://doi.org/10.1016/j.jmsy.2017.03.002

Zhu, J., Zhou, H., Wang, C., Zhou, L., Yuan, S., & Zhang, W. (2021). A review of topology optimization for additive manufacturing: Status and challenges. *Chinese Journal of Aeronautics*. https://doi.org/10.1016/j.cja.2020.09.020

Chapter 7
Short-Term Routing Models for COVID-19 Treatment Transfer Between Hospitals

Jebum Pyun, Seayoung Samantha Park, and Jiho Yoon

Abstract While technologies enable better observation and control over supply chain dynamics through visibility and real-time data analytics, the COVID-19 pandemic has intensified disruption-related challenges to supply chain network dynamics. Thus, these increased uncertainties and risks make it impossible to proactively predict the areas and sizes of surges in COVID-19 infections without limiting people's freedom of movement. This notion implies that we may need to focus on reactive planning to transfer COVID-19 treatment between hospitals and/or hospital systems. We introduce an optimization model for reactive short-term vehicle routings for such transfers. The optimization model proposed in this study can simultaneously grasp vehicle movement and cargo location information while minimizing the total travel time of vehicles, which can handle the urgency of treatment transfers by changing the value of the limited travel time of vehicles. Although the model does not include every condition that can be considered in the treatment transfers between hospitals, it shows the potential of the model we proposed in the transfer of treatment in case of shortages.

Keywords Routing · Scheduling · Domestic/local logistics · Optimization · Treatment for COVID-19

7.1 Introduction

The first round of supply shortages in the management of COVID-19 can be defined as a personal protective equipment (PPE) shortage. This shortage was addressed by rapidly reconfiguring all available resources to meet the unprecedented

J. Pyun
Hoseo University, Department of Big Data & Management Engineering, Asan, South Korea
e-mail: pjb@hoseo.edu

S. (Samantha) Park · J. Yoon (✉)
Chung-Ang University, School of Business Administration, Seoul, South Korea
e-mail: seayoung@cau.ac.kr; jihoyoon@cau.ac.kr

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_7

demand, as the resources were needed to fill the existing gap exist.[1] From a macro perspective, international logistics was considered to utilize links with other countries to secure the necessary supply if the crisis was not resolved promptly with domestic production and restocking of PPE. Thus, having a backup stream from an international source is a logistical issue. Similarly, from a micro perspective, we can consider domestic/local logistics to alleviate PPE shortages by rapidly sharing PPE among domestic/local hospitals and/or hospital systems.

There was also a shortage of vaccines, which can be defined as the second round of supply shortages in the management of COVID-19. However, this shortage was different from the PPE shortage in that the global supply was insufficient. Moreover, while PPE is an immediately needed supply, in the case of vaccines, the impact of shortages can be reduced by a reservation system. The only logistical issue with the vaccine supply was associated with the cold chain, which emphasizes low temperatures more than agility.

Among the treatments for COVID-19, only one drug called remdesivir has been approved by the F.D.A. for this disease, and studies have shown it may provide only modest benefits to patients. The F.D.A. has granted emergency use approval for other therapies, some of which have not yet been supported by results from large-scale, randomized clinical trials. That is, there is still no highly effective treatment.[2] Therefore, we now need to prepare for the third round in the management of COVID-19, i.e., shortages in the treatment of COVID-19. Regardless of the types of treatment for COVID-19 (i.e., whether temperature sensitive or not), these are similar to PPE in that they will need to be used immediately (i.e., time sensitive). Thus, if there is a shortage of these treatments, it is highly likely to be similar to a PPE shortage. As a result, we need to emphasize the importance of agility and reactiveness in international and domestic/local logistics.

Technologies allow to better observe and control supply chain dynamics (e.g., through visibility and real-time data analytics). On the other hand, the COVID-19 pandemic has highlighted the disruption-related questions of supply chain network dynamics and clearly demonstrated the key roles of dynamic control, adaptability, and viability in supply chain networks, both at the strategic and operational levels. Overall, modern and future supply chain networks are increasingly challenged by uncertainties and risks, multiple feedback cycles, adaptive mechanisms, and dynamics. Thus, it is clear that the proactive prediction of areas where COVID-19 infections will be skyrocketing and their sizes would almost be impossible without restricting people's freedom of movement. This notion implies that we may need to focus on reactive rather than proactive planning in terms of transferring COVID-19 treatment between hospitals and/or hospital systems.

Regarding PPE, some hospitals have had extras supplies, while others have not had enough. The Centers for Disease Control and Prevention (CDC) was working on a system that would track inventory across the USA. However, the main hurdle

[1] https://fortune.com/2020/04/07/coronavirus-ppe-supply-chain-loan/.

[2] https://www.nytimes.com/interactive/2020/science/coronavirus-drugs-treatments.html.

was not the technology. Rather, the issue was encouraging hospitals to become comfortable about sharing information on their preparedness—information that, until now, they have considered as confidential.[3] For this reason, in practice, the amount of PPE transferred and shared is negotiated and decided between hospitals and/or hospital systems rather than controlled by a central command center (e.g., government agencies such as the CDC), which can be faster and more effective in emergency situations such as the COVID-19 pandemic.[4]

Therefore, we need to develop a domestic/local logistics model with a fixed origin and destination, which should be a model that can simultaneously grasp the quantity and location of the treatment for COVID-19, along with scheduling the vehicle that transports it. Also, as discussed above, due to the nature of COVID-19 treatment, it should be a model focused on short-term planning (which is highly agile and responsive) rather than long-term planning.

7.2 Literature Review

Traditionally, the routing problem has been widely studied from the mathematical programming perspective, which is generally referred to as the vehicle routing problem (VRP) or vehicle scheduling problem (VSP). Mingozzi et al. (1999) utilize the exact algorithm of the VRP model in a central depot. In their study, they present a model in which each customer is visited once, with the condition that the customer of the linehaul must first be visited for customers consisting of the linehaul and backhaul. In order to minimize the total cost of the route, the model was proposed to plan m routes for each vehicle. That is, the VRP model for customers divided into two types became the basis for the network configuration of our model. However, while their model includes the premise that every customer must be visited once, our model does not include this condition. Put differently, in order to transport cargo, it is possible to visit any customer multiple times in our model.

Barbarosoglu and Ozgur (1999) considered a structural environment consisting of a two-level structure between (i) a parent company containing a plant and (ii) a distribution company. They proposed a mathematical model that addresses the single-depot VRP to transport products from the parent company to the main depot of the nearest distribution company and solve the shipping schedule at this depot. Freling et al. (2001) presented a mathematical model for a single-depot VSP considering the traveling time between paired locations, and Mesquita and Paixão (1999) introduced a mathematical model for the multi-depot VSP that minimizes scheduling costs by grouping a set of trips consisting of a timetable into vehicle blocks and allocating the vehicle blocks to m depots.

[3] https://www.npr.org/sections/health-shots/2020/03/12/813984872/coronavirus-pushes-more-hospitals-to-share-data-about-inventories-of-protective-.

[4] https://www.ruralhealth.us/blogs/ruralhealthvoices/october-2020/rural-leaders-build-network-to-source-ppe.

Further, Vehicle Problem with Pickups and Deliveries (VRPPD), an extension of VRPs, has been addressed for specific VRP cases. VRPPD consists of routing vehicles in order to satisfy a set of transportation requests and each request is defined by the size of the demand to be transported and the pickup and delivery vertices (Berbeglia et al., 2007; Parragh et al., 2006; Battarra et al., 2014). The cargo handled in the mathematical model proposed in our study is characterized by the fact that (i) the origin and destination for each transportation are fixed and (ii) the amount of treatment transported between hospitals is assumed to be known; this feature classifies our study as VRPPD. One of the most distinguishable characteristics of VRPPD is that it mitigates the imbalance in the distribution throughout the entire network or the insufficiency of supplies to certain nodes by relocation such as relocating shared vehicles (Chemla et al., 2013; Dell'Amico et al., 2014).

As discussed in the introduction section, our model focuses on short-term rather than long-term planning due to the features of COVID-19 treatment transfers between hospitals and/or hospital systems. In general, detailed demand forecasts can at best provide a reasonable basis for a short-term planning horizon, while long-term decision problems rely on aggregate data (Fink and Reiners, 2006). The application of our model is for urgently needed items and their transfers rather than production. Thus, aggregate demand data are not available or effective.

Moreover, Meng et al. (2012) indicated that matching estimated demand precisely to realized demand is almost impossible, which implies that the uncertainty of demand should be incorporated into short-term planning. Similarly, Chew et al. (2006) emphasized the importance of short-term planning under high demand uncertainty. Rahman et al. (2019) also claim that under deep uncertainty, multiple repeated short-term logistics plannings can be more effective than a long-term planning. In addition, Nasrabadi et al. (2020) classify fluctuations in demand as short-term uncertainty in healthcare system planning. Particularly, in emergency situations such as the COVID-19 pandemic, an immediate response is key. In such circumstances, an immediate short-term response is more important than increasing the level of certainty in demand. Berkoune et al. (2012) emphasized that requests during such emergency situations must be scheduled immediately. Liu et al. (2018) also stressed in their study that providing relief promptly is crucial in emergency logistics. Therefore, from this point-of-view, we develop a mathematical model from the short-term planning perspective.

7.3 Models

7.3.1 Problem Definition

The problem to be solved in this study can be viewed as a scheduling and routing problem. In practice, the transfer of patients between hospitals is directed by hospitals, and not by the central command center. In this regard, it can be speculated that the transfer of COVID-19 treatment will take place between hospitals and/or hospital systems. Therefore, we note that the amount of treatment transferred between certain hospitals is regarded as given information.

There is information concerning the amount of treatment that must be transferred from one hospital to another, which is determined by the hospitals. Based on this treatment cargo volume information, all these cargo shipments should be transported by vehicles distributed in different locations. The number of vehicles available per a certain period of time (e.g., day, half a day, quarter of a day) is predetermined, and each vehicle is dispersed in different locations (hospitals). We try to minimize the total transportation costs of vehicles (or total transportation time spent with vehicles) by matching the vehicles based on the treatment cargo volume and vehicle information. Each vehicle can load and transport a limited capacity of cargo and may visit the same area multiple times for delivery. The point is that the cargo handled here must be transported to another area. In other words, it has the characteristic of cargo with a predetermined origin and destination.

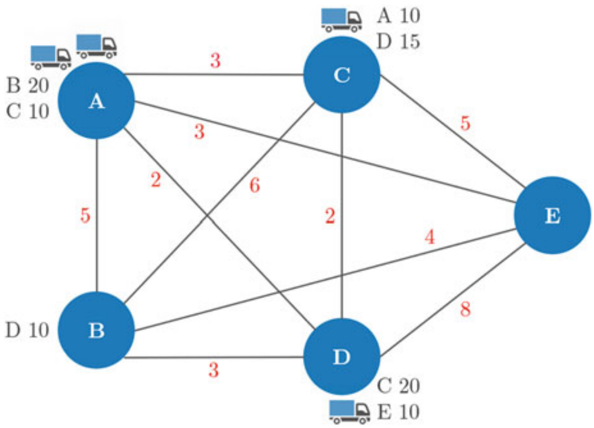
Our model is defined as a vehicle scheduling problem that can identify the quantities of treatment transported by vehicles, and the location information of vehicles and cargo based on the previously presented cargo and vehicle information. The objective of the problem is to minimize the cost (time) of transporting all cargo by vehicles moving from each hospital, as described above. At the same time, knowing the location of the vehicle carrying the cargo and the location of the cargo is key to solving the problem. Based on the above explanation, we propose one example problem.

As shown in Table 7.1, there are 7 shipments with treatment cargo volume information. Each shipment has a fixed origin and destination, and the amount to be transported is indicated. Note that for simplicity, we assume that there is only one type of treatment, i.e., the items transported are identical. Someone can raise questions about the information in Table 7.1. For example, while hospital A sends 10 units of treatment to hospital C, hospital A receives 10 units of treatment from hospital C, which is inefficient. However, this type of operational inefficiency can be caused by human error, system error, etc. In this study, correcting this type of inefficiency is beyond the scope of this study, and thus will be ignored. Table 7.1 provides information on the amount of cargo and shows that all these cargo shipments should be delivered to their destinations with vehicles distributed

Table 7.1 Example of cargo volume information

Commodity	Origin	Destination	Quantity
1	A	B	20
2	A	C	10
3	B	D	10
4	C	A	10
5	C	D	15
6	D	C	20
7	D	E	10

Fig. 7.1 Example problem for the proposed model



in each area. Based on this idea, a schematic model (as shown in Fig. 7.1) can be constructed.

In Fig. 7.1, 5 hospitals (nodes) are established, and the road network connecting these hospitals and the travel distance (cost) of the vehicles using the road network are indicated. The vehicles are distributed and deployed in each area, as shown in Fig. 7.1. As previously defined, information on the cargo with a fixed destination is given for each region. Also, as mentioned earlier, all treatments must be transported to the appropriate hospitals. The aim of doing so is to determine the location of the transported treatments and the vehicle while minimizing the transport distance (time) of the vehicle. In other words, the problem involves figuring out which vehicle is carrying how much treatment, and where it is being transported.

Here, we would like to express the initial position of the vehicles mathematically and think about it by modifying the above model in order to clearly understand the supply and demand. We divide each node into a node responsible for the demand and a node responsible for the supply, and add a virtual depot O, which is the hypothetical initial location of the vehicles. The treatment cargo volume information shown in Table 7.1 is transformed as shown in Table 7.2.

Table 7.2 Modified cargo volume information

Commodity	Origin	Destination	Quantity
1	A+	B−	20
2	A+	C−	10
3	B+	D−	10
4	C+	A−	10
5	C+	D−	15
6	D+	C−	20
7	D+	E−	10

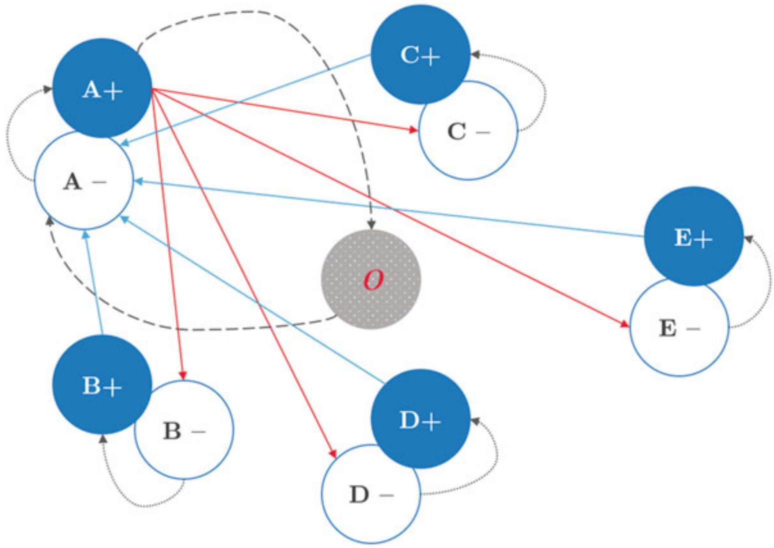


Fig. 7.2 Example problem for the proposed model

In Table 7.2, nodes with "+" represent supply hospitals, while nodes with "−" represent demand hospitals. Based on the above explanation, the problem shown in Fig. 7.1 can be transformed into the problem shown in Fig. 7.2. The modified model of Fig. 7.2 is compared with the model of Fig. 7.1 and is explained as follows.

Figure 7.2 is expressed as being centered on node A. As discussed above, each node is divided into a node in charge of the demand and a node in charge of the supply. We assume that the vehicle is located at the initial virtual depot O, and all vehicles enter the "−" node and exit the "+" node. The distance between each demand node and supply node is the same as the distance presented in Fig. 7.1. In order for the model in Fig. 7.2 to have the same meaning as the model in Fig. 7.1, some assumptions are required. Here is a list of the assumptions:

1. In the virtual depot O, the cost of a vehicle leaving for the "−" node is zero.
2. Vehicle transport is done from the "+" node to the "−" node.
3. Vehicles entering the "−" node exit from the "+" node of the same index.
4. The cost of moving from a "−" node to a "+" node of the same index is zero.

Through these assumptions, the models in Figs. 7.1 and 7.2 can become models with the same meaning. Through these model changes and assumptions, we will propose an optimization model in the next chapter. The mathematical model proposed in this study aims to solve VRPPD given that the objective is to identify the optimal routing while satisfying the transportation requests that have fixed pickup and delivery (destination) points.

7.3.2 Mathematical Model

The previously proposed model (as shown in Fig. 7.2) is defined as a directed graph of $G = (V, A)$. Here, $V = O \cup N$, O denotes a virtual depot, and N denotes each node (hospital). Again, N is divided into a node in charge of the supply and a node in charge of the demand, so we define it as $N = N^+ \cup N^-$. N^+ represents the hospital responsible for the supply, and N^- represents the hospital responsible for the demand. According to the rule of Assumption 2 discussed above, the virtual depot O will also be classified as O^+ for the virtual depot from which the vehicle exits, and O^- for the virtual depot O from which the vehicle enters. Therefore, the node where the vehicle exits can be defined as $V^+ = N^+ \cup O^+$, and the node where the vehicle enters can be defined as $V^- = N^- \cup O^-$. The variables and parameters additionally required to establish the MCVSP mathematical model proposed in this study are as follows:

Variables	
$x^v_{(i,j)k}$:	Amount of treatment k that vehicle v transports using arc (i, j)
u^v_{ij} :	Binary variable for whether vehicle v moves using arc (i, j)
Parameters	
c_{ij} :	Traveling cost (distance) of the vehicle using arc (i, j)
$k = (i, j)$:	Commodity at source i and destination j
K :	Set of commodities
d_k :	Amount of treatment k that must be transported
Q_v :	The limited capacity of the vehicle v
S :	The limited distance vehicle v can travel in a period of time
V_i :	Number of vehicles moving from node (virtual depot) O to node (hospital) i
M :	Big M

The model has two types of decision variables; the amount of treatment that vehicle v carries and whether vehicle v moves on arc (i, j). The objective function and constraints expressed by the decision variables and parameters are as follows:

$$\text{Minimize} \quad z = \sum_{v \in V} \sum_{i \in N^+} \sum_{j \in N^-} c_{ij} u^v_{ij}$$

subject to

$$\sum_{v} \sum_{j \in N^- \setminus \{i^-\}} x^v_{(i,j)k} = d_k, \qquad \forall i \in N^+, \ \forall k \in K \tag{7.1}$$

$$\sum_{v} \sum_{j \in N^+ \setminus \{i^+\}} x^v_{(j,i)k} = d_k, \qquad \forall i \in N^-, \ \forall k \in K \tag{7.2}$$

$$\sum_{v} \sum_{j \in N^- \backslash \{i^-\}} x^v_{(i,j)k} - \sum_{v} \sum_{l \in N^+ \backslash \{i^+\}} x^v_{(l,i)k} = 0, \qquad \forall i \in N, \ \forall k \in K \tag{7.3}$$

$$\sum_{j \in N_0^+ \backslash \{i^+\}} u^v_{ji} - \sum_{l \in N_0^- \backslash \{i^-\}} u^v_{il} = 0, \qquad \forall i, \ \forall v \tag{7.4}$$

$$\sum_{j \in N^-} u^v_{O^+ j} = 1, \qquad \forall v \tag{7.5}$$

$$\sum_{j \in N^+} u^v_{jO^-} = 1, \qquad \forall v \tag{7.6}$$

$$\sum_{v} u^v_{Oi} = V_i, \qquad \forall i \in N^- \tag{7.7}$$

$$\sum_{v} \sum_{i \in N^-} u^v_{Oi} = \sum_{v} \sum_{j \in N^+} u^v_{jO} \tag{7.8}$$

$$\sum_{k} x^v_{(i,j)k} \leq Q_v, \qquad \forall i \in N^+, \ \forall j \in N^-, \ i \neq j, \ \forall v \in V \tag{7.9}$$

$$\sum_{k \in K} x^v_{(i,j)k} \leq M \cdot u^v_{ij}, \qquad \forall i \in N^+, \ \forall j \in N^-, \ i \neq j, \ \forall v \in V \tag{7.10}$$

$$\sum_{i \in N^+} \sum_{j \in N^-} c_{ij} u^v_{ij} \leq S, \qquad \forall v \tag{7.11}$$

$$u^v_{ij} \in \{0, 1\}, \qquad \forall i, \ \forall j, \ \forall v \tag{7.12}$$

$$x^v_{(i,j)k} \geq 0 \tag{7.13}$$

The objective function aims to minimize the sum of the travel costs of all vehicles. Note that the cost indicates that total distance, which can be translated into the total travel time. Thus, the objective function can be translated into the minimization of the sum of the travel time of all vehicles.

Constraints (1), (2), and (3) satisfy the workflow conservation rule. More specifically, constraint (1) is an expression meaning that the treatments in each hospital must be transported from the origin to another hospital. Constraint (2) indicates that all treatments transported from the origin must all arrive at the destination. Constraint (3) implies that if a vehicle moves to a hospital that is not a demand node of a commodity (in order to minimize the cost of moving), all incoming treatments must leave.

Constraints (4) to (8) are related to vehicle movement. Constraint (4) is an expression indicating that all vehicles entering each node must leave, while constraint (5) indicates that all vehicles must move to only one node from the virtual depot O assuming that the vehicle is initially located. Constraint (6) means that all vehicles must enter the virtual depot O from only one hospital. Constraint (7) expresses a vehicle's initial position, while constraint (8) indicates that the number of vehicles entering and leaving the virtual depot O must be the same.

Constraint (9) is an expression indicating that the cargo capacity to be transported cannot exceed the loading capacity of the vehicle, whereas constraint (10) indicates whether or not the vehicle is used. Constraint (11) represents a restriction on the moving cost (travel time) of a vehicle.

7.4 Experiments

In this section, we will present the results of a computational experiment in which some numerical data are input using the mathematical model proposed in the previous section.

7.4.1 Experiment 1

Experiment 1 was conducted without limiting the travel distance of the vehicle. There are 5 hospitals and 4 vehicles. There are 6 shipments with treatment cargo information, and the loading capacity is 30 for all vehicles. Table 7.3 shows the input data of the treatment used in Experiment 1.

This problem consists of 592 decision variables and 222 constraints. The experimental results are calculated as the data from which the following information can be inferred. The experimental results can be schematically shown in Fig. 7.3. The number in the square represents the vehicle number, the alphabet in the circle represents each hospital, and the number in parentheses represents the moving cost (travel time) of the vehicle. For example, in the case of vehicle 3, the vehicle's routing is configured as follows, and the quantity of the commodity transported at that time is as shown in the diagram. In Fig. 7.1, initially, two vehicles are located at node A, one vehicle is located at node C, and another vehicle is located at node D. The minimized travel time for this experiment is 16, which is the result of an efficiency-focused model. A schematic diagram of the results for Experiment 1 is shown in Fig. 7.3.

Table 7.3 The origin and destination of treatment for Experiment 1, and the quantity transported

	Destination				
Origin	A	B	C	D	E
A	–	–	20	15	–
B	–	–	–	–	–
C	10	–	–	–	15
D	10	–	20	–	–
E	–	–	–	–	–

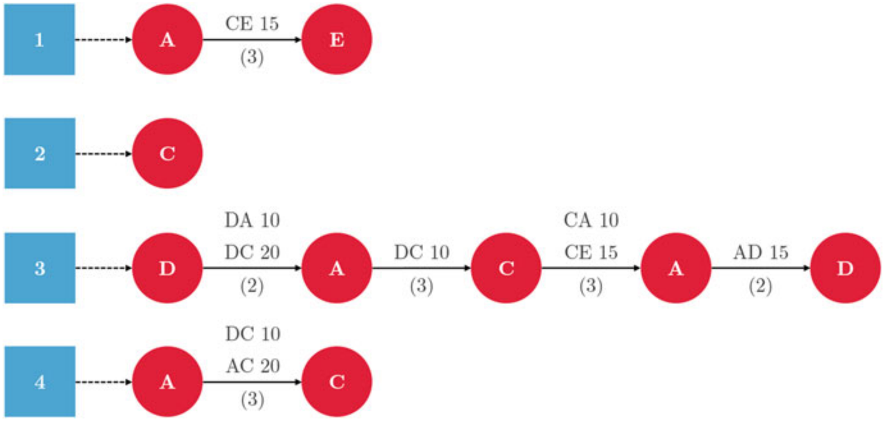


Fig. 7.3 Result of Experiment 1

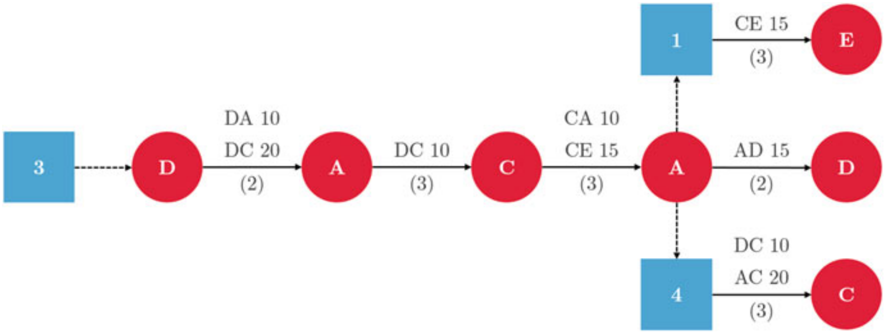


Fig. 7.4 Integrated result of Experiment 1

Figure 7.3 shows the routing and commodity quantity for each vehicle. Based on this information, the results of Experiment 1 can be summarized as shown in Fig. 7.4.

In Fig. 7.4, if the movement of the vehicles is not restricted, i.e., focusing on efficiency only, there may be cases where the available vehicles cannot be used properly. This means that some hospital(s) may have to wait a long time to receive urgently needed treatment, e.g., Hospital E has to wait for 11 units of time to receive the 15 units of treatment from Hospital C. Thus, it appears that it was necessary to use the vehicle more effectively by setting the vehicle's travel time limit; thus, Experiment 2 was conducted with the vehicle travel time limit using the above data.

7.4.2 *Experiment 2*

In Experiment 1, which was performed previously, an unbalanced result was obtained in the use of a vehicle. In order to solve this problem, the vehicle travel distance (time) was limited for each vehicle. The input data are the same as in Experiment 1, and the movement distance limit for each vehicle is set to 8. In this case, there are 592 decision variables and 226 constraints. This problem minimizes the total vehicle travel time to 16 units of time, which is the same objective function value as that of Experiment 1. Figure 7.5 shows the routing and commodity quantity for each vehicle in Experiment 2.

As can be seen in Fig. 7.5, the imbalance in vehicle use (as shown in Experiment 1) is resolved to some extent. In Experiment 1, vehicles 1, 3, and 4 are used for 3, 10, and 3 units of time, respectively. As a result, hospitals D and E should wait for 10 and 11 units of time to receive the treatments from hospitals A and C, respectively. However, in Experiment 2, vehicles 1, 2, and 3 are used, and the corresponding travel times are 3, 6, and 7, respectively. The relieved vehicle usage imbalance also relieves the delivery time imbalance. In Experiment 2, hospitals D and E can receive the treatments in 2 and 6 units of time, respectively.

Of course, the delivery time for some hospitals will increase. For example, hospital A could receive 10 units of treatment in 2 units of time in Experiment 1, but it would take 4 units of time in Experiment 2. However, overall, it can be said that the delivery time imbalance is reduced in Experiment 2 compared with the result of Experiment 1. Putting this together, the result can be schematically shown in Fig. 7.6.

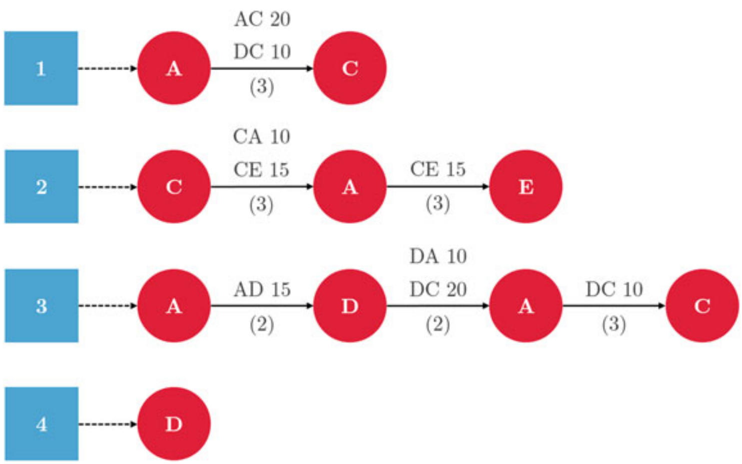


Fig. 7.5 Result of Experiment 2

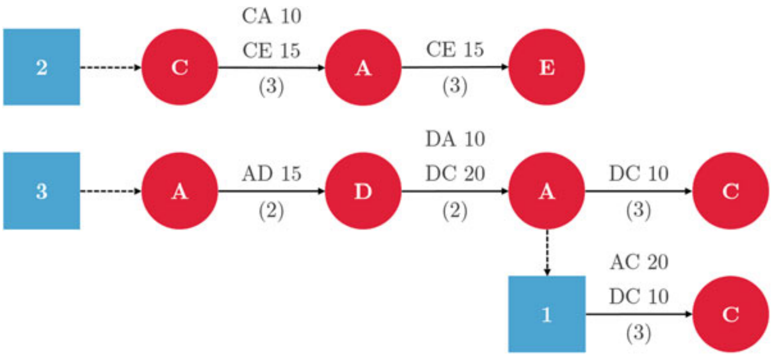


Fig. 7.6 Integrated result of Experiment 2

Table 7.4 The origin and destination of the commodity for Experiment 3, and the quantity transported

	Destination						
Origin	A	B	C	D	E	F	G
A	–	15	–	–	–	–	–
B	–	–	–	–	–	–	–
C	10	–	–	–	–	–	15
D	–	15	–	–	–	–	–
E	–	–	–	–	–	–	–
F	–	–	–	10	20	–	–
G	–	–	–	10	–	–	–

7.4.3 Experiment 3

Now, we can consider the situation where the severity of the shortage is less than that of Experiments 1 and 2. Moreover, if the handling conditions of the treatment are not as stringent as those of the vaccines, the treatment transfers between hospitals will be more frequent and the number of vehicles available for these transfers may increase. Thus, Experiment 3 was conducted in a situation where a small number of goods had to be transported to various hospitals, and there were many available vehicles.

Transportation can be done using vehicles located in each hospital, but in that case, the cost of moving the vehicle is wasted. The main purpose is to transport all treatments while minimizing vehicle movement. The problem was established in consideration of this situation. There are 7 nodes and 9 vehicles, and the vehicle capacity is established differently. The vehicle travel distance (time) limit is set to 20, and the commodity information is shown in Table 7.4. This problem consists of 3141 variables and 902 constraints.

The results of Experiment 3 are summarized, as shown in Fig. 7.7. All transfers can be completed using 3 out of 9 vehicles. A small-capacity truck is used to transport the treatment that should be transported from several hospitals to one place, and a large-capacity truck is used to transport the collected treatments to

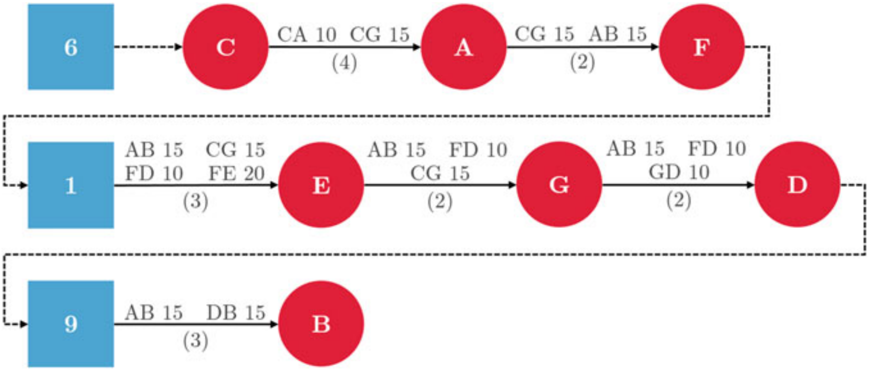


Fig. 7.7 Integrated result of Experiment 3

several hospitals. This is the same result when thinking intuitively. The minimum total vehicle travel time in this case is 16.

Note that we can easily modify the value of the vehicle travel distance limit (S), as done in Experiment 2, if the urgency is very important. Intuitively, as the value of S decreases, the number of vehicles used in the transfers will increase and the average delivery time between two hospitals will decrease. It can also be expected that deliveries will be made via direct delivery rather than indirect delivery.

7.5 Conclusion

While technologies enable better observation and control over supply chain dynamics through visibility and real-time data analytics, the COVID-19 pandemic has intensified disruption-related challenges to supply chain network dynamics. That is, it is almost impossible to pre-emtively predict areas where the number of COVID-19 infections will be rapidly increasing unless people's freedom of movement is strictly controlled. Thus, it may be necessary to focus on reactive rather than proactive planning for transferring COVID-19 treatments between hospitals and/or hospital systems. In practice, the amount of transferred and shared treatments for COVID-19 will be decided by hospitals and/or within hospital systems rather than by a central command center (such as the CDC) in case of treatment shortage situations as witnessed in PPE shortages.

In this study, we apply an optimization model (VRPPD) for reactive short-term vehicle routing. The optimization model proposed in this study can simultaneously grasp vehicle movement and cargo location information while minimizing the total travel times of vehicles. As an application of the model, we consider COVID-19 treatment transfers between hospitals and/or hospital systems. This model can handle the urgency of treatment transfers by changing the value of the limited travel time of vehicles, as shown in Experiment 2. Even though we did not include some detailed conditions that can be considered in treatment transfers between hospitals, this model shows the potential use of optimization models for treatment transfers in case of treatment shortages.

Even though the current model shows some potential, several points can be considered for future study. The current model considers only one type of treatment, but it is likely that multiple types of treatment for COVID-19 exist that require different delivery conditions. In addition, our model dose not correct for human and/or systemic errors that may be present in data regarding treatment cargo information. However, by adding appropriate constraint(s), errors in the input data can be corrected.

References

Barbarosoglu, G., & Ozgur, D. (1999). A tabu search algorithm for the vehicle routing problem. *Computers & Operations Research, 26*(3), 255–270.

Battarra, M., Cordeau, J.-F., & Iori, M. (2014). Chapter 6: Pickup-and-delivery problems for goods transportation. In *Vehicle routing: Problems, methods, and applications* (2nd ed., pp. 161–191). Philadelphia: SIAM.

Berbeglia, G., Cordeau, J.-F., Gribkovskaia, I., & Laporte, G. (2007). Static pickup and delivery problems: A classification scheme and survey. *Top, 15*(1), 1–31.

Berkoune, D., Renaud, J., Rekik, M., & Ruiz, A. (2012). Transportation in disaster response operations. *Socio-Economic Planning Sciences, 46*(1), 23–32.

Chemla, D., Meunier, F., & Calvo, R. W. (2013). Bike sharing systems: Solving the static rebalancing problem. *Discrete Optimization, 10*(2), 120–146.

Chew, E. P., Huang, H. C., Johnson, E. L., Nemhauser, G. L., Sokol, J. S., & Leong, C. H. (2006). Short-term booking of air cargo space. *European Journal of Operational Research, 174*(3), 1979–1990.

Dell'Amico, M., Hadjicostantinou, E., Iori, M., & Novellani, S. (2014). The bike sharing rebalancing problem: Mathematical formulations and benchmark instances. *Omega, 45*, 7–19.

Fink, A., & Reiners, T. (2006). Modeling and solving the short-term car rental logistics problem. *Transportation Research Part E: Logistics and Transportation Review, 42*(4), 272–292.

Freling, R., Wagelmans, A. P., & Paixão, J. M. P. (2001). Models and algorithms for single-depot vehicle scheduling. *Transportation Science, 35*(2), 165–180.

Liu, Y., Lei, H., Zhang, D., & Wu, Z. (2018). Robust optimization for relief logistics planning under uncertainties in demand and transportation time. *Applied Mathematical Modelling, 55*, 262–280.

Meng, Q., Wang, T., & Wang, S. (2012). Short-term liner ship fleet planning with container transshipment and uncertain container shipment demand. *European Journal of Operational Research, 223*(1), 96–105.

Mesquita, M., & Paixão, J. (1999). Exact algorithms for the multi-depot vehicle scheduling problem based on multicommodity network flow type formulations. In *Computer-aided transit scheduling* (pp. 221–243). Berlin: Springer.

Mingozzi, A., Giorgi, S., & Baldacci, R. (1999). An exact method for the vehicle routing problem with backhauls. *Transportation Science, 33*(3), 315–329.

Nasrabadi, A. M., Najafi, M., & Zolfagharinia, H. (2020). Considering short-term and long-term uncertainties in location and capacity planning of public healthcare facilities. *European Journal of Operational Research, 281*(1), 152–173.

Parragh, S. N., Doerner, K. F., & Hartl, R. F. (2006). A survey on pickup and delivery models part II: Transportation between pickup and delivery locations. *Journal für Betriebswirtschaft, 58*, 81–117.

Rahman, M. T., Majchrzak, T. A., & Comes, T. (2019). Deep uncertainty in humanitarian logistics operations: Decision-making challenges in responding to large-scale natural disasters. *International Journal of Emergency Management, 15*(3), 276–297.

Chapter 8
AI-Enhanced Maintenance for Building Resilience and Viability in Supply Chains

Fazel Ansari and Linus Kohl

Abstract In the era of Industry 4.0, supply chain management still faces the challenge of operating with increasingly complex networks under high uncertainty. These uncertainties influence decision-making processes and change the balance in the supply chain. Enterprise, therefore, strives to enable data-driven decision-making by increasing the digitalization and intelligentization of their processes. Artificial Intelligence (AI) approaches in particular can reinforce enterprises to proactively respond to changes and problems in the supply chain at an early stage and thus plan ahead. Utilizing predictive analytics and semantic modeling may improve target performance metrics, increases flexibility, and enables the development of a resilient and viable supply chain. This chapter provides an AI-enhanced approach for integrative modeling and analysis of related Key Performance Indicators (KPIs) toward building resilience and viability in manufacturing and supply chains, aided by Dynamic Bayesian Networks (DBN).

Keywords Artificial intelligence · Bayesian networks · Maintenance · Resilience · Efficiency · Sustainability

8.1 Introduction

Enterprises obtain goods and services in complex, global Supply Chains (SC). SC systems consist of four closely interrelated elements: Suppliers, manufacturing, distribution network, and customers. Each of these elements affects the behavior and performance of the entire system. This results in the necessity to consider all interactions, limitations, and uncertainties when making decisions for running a profitable SC. In recent years, research in the area of SC has predominantly

F. Ansari (✉) · L. Kohl
Research Group of Smart and Knowledge-Based Maintenance, TU Wien, Vienna, Austria

Fraunhofer Austria Research GmbH, Vienna, Austria
e-mail: fazel.ansari@tuwien.ac.at; linus.kohl@tuwien.ac.at

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_8

focused on the nature of the relationships and processes in a closed loop, circular environment (Golan et al., 2020). Real-world environments require the consideration of uncertain behavior, for example, of competitors, suppliers, and customers. However, uncertainty cannot be appropriately predicted or expected (Knight, 2014). In SC, two basic approaches of uncertainty can be differentiated, referring to (1) the decision-making process and (2) shifted balance and changed profitability. In the former case, a planner has not all needed information to form an informed decision. This can come from a lack of transparency, missing information, and the unknown impact and interrelations of actions. The latter case is caused by potential unpredictable events such as pandemic, social or economic instabilities (Bonde, 2018). Consequently, enterprises aim for the use of systems that facilitate making better and more informed decisions. Large amounts of data are needed to make those systems possible. This data can then be used to develop Artificial Intelligence (AI) models. Especially in the field of Supply Chain Management (SCM), countless use cases for AI can be found. As a result, large enterprises have started experimenting with AI solutions very early on, to better understand how their business works and what events are most likely to happen in the future. This is also reflected in a study by Gartner, which shows that 72% of all study participants find investments in digitization as a competitive advantage (Klappich & Muynck, 2020). Results of this early phase of experimenting are now available on the market from SC application vendors. State-of-the-art AI tools have the ability to analyze large amounts of data, clean and identify patterns, themes, and trends and generate related action plans. This is achieved in either a predictive or prescriptive manner (Klappich & Muynck, 2020). As of today, there are two main options that allow enterprises to perform analyses in their SCs. The first option is the traditional platform approach is based on an integrated control tower capability, which is part of the SCM platform. This platform supports a combination of SC planning and execution. A supply chain control tower (SCCT) is a notable example, i.e., a central date hub and customized dashboard of data, key business metrics, and events across, that captures the necessary technologies, organizations, and processes, and accumulates required data for short- and long-term decisions (Rölli, 2021). The second option in the field of SCM is the data lake approach, which mainly relies on the visualization of data. In contrast to business intelligence, where analysis models would be built based on the data lake to enable deeper insights, a data lake is a repository that stores the collected data in its natural format, i.e., raw and unprocessed format (Giebler et al., 2020).

Disruptions in an SC can occur due to various reasons. It can be a breakdown in a production line, IT problems, demand fluctuations, strikes, war, changes in the legal framework, environmental conditions or pandemics, e.g., COVID-19 (Ivanov, 2020; Scholten et al., 2020). Some of the aforementioned disturbances are in advance predictable and even controllable. However, there are also uncontrollable disturbances. The impact of a disturbance on the performance of an SC depends strongly on the duration and severity of the event. It should, therefore, be the goal of an enterprise to be particularly resilient to such disruptions (Scholten et al., 2020).

Supply chain resilience (SCRes) is an extremely important strategic tool for gaining a market advantage. SCRes is the ability of organizations to withstand disruptions and disturbances with no, or limited performance deterioration (Christopher & Peck, 2004). The importance of SCRes is particularly highlighted by a study of the World Economic Forum (Bhatia et al., 2013), which shows that 80% of enterprises are concerned about the resilience of their SC. In the "Resilien-Tech" project by acatech (2014), lessons learned were defined in seven topic areas in order to be able to develop a resilient enterprise, as well as regulatory requirements. The topic areas include (1) development of regulations on the interface between the state and the private sector, (2) implementations of insurance obligations, (3) conduct of resilience monitoring and incentivization, (4) introduction of early warning system and mandatory reporting, (5) use of incentive systems, (6) introduction of regulations for the implementation of emergency and crisis exercises, and (7) evaluation of cyber risks. These topic areas are defined in a vertical structural going from macro perspective of regulatory government frameworks for dealing with complex (systems of) systems in order to increase resilience, to the micro perspective of the SC where machine breakdowns and subsequent production line failures can lead to the need to anticipate unpredictable events. The ability to quickly adapt to disruptions and produce the same quality and quantity despite unexpected events becomes an even more important challenge after COVID-19 in today's agile business world. This can be highlighted due to a study by Capgemini (2020), which shows that it took 68% of manufacturing enterprises 3 months to recover from SC disruptions caused by COVID-19.

An emerging dimension in the consideration of supply chain is viability. This is defined by Ivanov (2020) as "the ability of a supply chain (SC) to maintain itself and survive in a changing environment through a redesign of structures and replanning of performance with long-term impacts." The Viable Supply Chain (VSC) comprises three dimensions: agility, resilience, and sustainability. Ivanov and Dolgui (2021) designed a conceptual framework for VSC with a focus on aligning resilience, sustainability, profitability, and digitalization.

The increase of the robustness and resilience of the production and thus of the SC can be ensured by appropriate maintenance leading to achieve and preserve desired uptime (i.e., low failure rate) of machine and plant as well as production system. This enables flexible resource management and keeps losses to a minimum. This is further reinforced by the fact that modern production systems are complex interactions of production machines, sensors, and IT systems, which in turn represent complex, self-contained systems. So-called Cyber Physical Production System (CPPS) consist of autonomous and cooperative elements as well as subsystems (Monostori et al., 2016). These subsystems are interconnected through and within all levels of production and logistic networks (Ansari et al., 2018). CPPS have three main characteristics, (1) intelligence (smartness), (2) connectedness, and (3) responsiveness, which enable viable production and impact VSC (Panetto et al., 2019). In other words, prediction of machine and plant breakdowns should be considered for modeling and estimation of SCRes. This can be achieved through the use of AI methods and technologies as well as knowledge-based maintenance methodologies in particular predictive and prescriptive maintenance (Ansari et al., 2019; Ivanov et al., 2021a, 2021b). In addition to predicting machine breakdowns, AI-enhanced maintenance must also recommend actions, as in prescriptive maintenance, in order to be able to react flexibly to changes. Predictive analysis in the context of SCM and production planning focuses on historical dataset and retrospective analysis to extract patterns used to forecast planning and scheduling. This allows management to increase flexibility and robustness as the core values of a SCRes. Hence, AI contributes to the predictability of risk, reduce risk in manufacturing enterprises and thus reduce uncertainty in SC. Based on the prediction of future events, prescriptive analysis makes it possible to act optimally in response to disturbances, disruptions, and changes. Using a diverse set of methods including mathematical modeling, simulations, statistical learning, machine learning, and semantic technologies (e.g., Knowledge Graphs, Bayesian Networks), prescriptive analytics enables the development of flexible and robust plans that take uncertainties into account. Nevertheless, the application of AI in SCM and production and logistics management does not end with planning and scheduling. AI can also implement recommendations leading to more responsive and flexible SC. This is especially relevant when real-time rescheduling is needed. AI systems dealing with dynamic time series data need to be able to constantly adopt to changing conditions and reflect them in decision-making parameters, preferences, and recommendations. This includes adopting equipment parameters and processes resulting in a range of alternative schedules. Accordingly, AI can either recommend those plans or schedule them automatically depending on the degree of automation. AI systems for prescriptive maintenance should consequently be able to work with a temporal component in addition to a complex, uncertain system in order to be able to realize resilient manufacturing and ultimately, building resilience in SCs. This failure resistance can be achieved by focusing on the concept of Reliability, Availability, Maintainability, and Safety (RAMS). Concentrating on reliability and availability in particular, major improvements can be made in industrial maintenance using prescriptive maintenance. The achieved improvement is evaluated using metrics and Key Performance Indicators (KPI). The most important of these are the Remaining Useful Lifetime (RUL), Mean-time Between Failure (MTBF), and Uptime. These KPIs have an impact on the Overall Equipment Efficiency (OEE) of production systems. An improvement of the OEE, therefore, leads to an increase in the reliability of manufacturing processes and thus to improved resilience in the SC (Karl et al., 2018). In particular, industrial AI and the associated ability to adapt itself can improve the aforementioned KPIs and lead to the ultimate goal of SCRes (Esmaeel et al., 2018). Notably, Ivanov et al. (2021b) proposed a three-dimensional framework for analyzing the impact of AI methods on SC.

Considering the above discussion into account, this paper provides an AI-enhanced approach for integrative modeling and analysis of related KPIs toward building resilience and viability in manufacturing and SCs, aided by Dynamic Bayesian Networks (DBN).

The rest of the paper is structured as follows: Sect. 8.2 provides a brief literature review discussing current research in the area of (1) resilience in SCM as well as (2)

Dynamic Bayesian Networks (DBN). Section 8.3 presents an application of a DBN in an industrial maintenance use case. Section 8.4 discusses the results, limitations, and possibilities of the proposed AI-enhanced approach. Finally, Sect. 8.5 explores the current state of applications of DBN as well as future outlooks in SCM.

8.2 Literature Analysis

8.2.1 Resilience and Viability in Supply Chain Management

The study of the impact of economic, environmental, geopolitical, societal, and technical uncertainties on SC is being closely examined in research by public organizations (World Economic Forum, 2017). Yet, tools for measurable monitoring and deduction in the form of KPIs to derive recommendations for action and consequent improvement of SCM are needed. The relationship between KPIs and SCRes has been examined by Karl et al. (2018). They divided the influence of KPIs on SCRes into three phases: (1) before, (2) during, and (3) after the disruption phase. The consequent literature analysis showed a very strong correlation between non-financial KPIs and resilience. In particular, KPIs for order and delivery times, inventory levels and customer satisfaction have been identified as suitable indicators that support resilience. A study by Werner et al. (2021) in the manufacturing sector shows that the optimization of non-financial KPIs can greatly increase the resilience of enterprises as well. It also reveals that monitoring KPIs can help to detect early signs of vulnerability and to take targeted actions.

Pursuing this line of research, it is important to design the strategy from three points of view: (1) identifying the KPIs for building resilience strategy, (2) classifying the KPIs to identify which actions should be taken to respond in the event of a disruption, and (3) developing contingency plans based on the identified KPIs. The issue of a quantitative assessment of SC reliability, resilience, and viability has been investigated by Chen et al. (2017) and Ivanov (2022) leading to the development of a unified framework for evaluating SC reliability and resilience. Stavropoulos et al. (2020) have established a corresponding decision-making framework after analyzing the manufacturing processes of medical equipment in the COVID-19 pandemic.

Weichhart et al. (2021) focused on adaptivity in resilient manufacturing, which can be implemented in three levels, namely (1) the use of robotics for intra-logistics, (2) a planning system that can reschedule manufacturing on an ad hoc basis, and (3) a modular process model and execution system to ensure adaptivity at the process level. Bauer et al. (2021) emphasize that AI is an enabler to increase the performance of SCs, as heuristic models can be used to understand the complex nature of such networks. Machine Learning (ML) in particular is well suited for this purpose as it allows for generalization and works very well with previously unknown data. The use of algorithms to improve resilience in complex industrial CPPS has been also investigated by Stavropoulos (2020). Here, they adopted a chaos engineering approach to ensure the requirements of available, secure, safe, and reliable system operation. Industrial AI and its impact on KPIs have been studied in detail by Bai et al. (2021) in the use case of truck platooning. In analytical experiments, a positive correlation was found between the AI model used and related KPIs, namely Availability, Mean Time to Failure (MTTF), and Mean Security Capacity to Failure (MSCF). Reliability and availability are particularly important here as parts of RAMS. The RAMS process can be used to analyze potential hazards and the effects of failures. This also includes Failure Mode and Effects Analysis (FMEA). As described in Passath et al. (2021), the RAMS process can be extended to include an asset criticality analysis. This asset criticality is then used as a parameter of a DBN, which enables the calculation of relevant KPIs over the product life cycle using an additional, temporal dimension. Considering the correlation between resilience and operational KPIs like availability as well as financial KPIs like profitability, Schenkelberg et al. have investigated the impact of maintenance on profitability using various AI methods like Bayesian Networks (Schenkelberg et al., 2020a), supervised ML (Schenkelberg et al., 2020b) and simulation (Schenkelberg et al., 2020c), respectively. Due to the advantage of BNs on combining expert opinions and data for integrative modeling and analysis of KPIs over time, this paper mainly explores BNs application for building resilience in manufacturing and SCs.

8.2.2 Dynamic Bayesian Networks

A Bayesian Network (BN) is a graphical model that represents probabilistic relationships between variables. A BN consists of a qualitative and a quantitative part. The qualitative part consists of directed, acyclic graphs. Here, each variable presents a node. A causal relationship between nodes is modeled with edges. The quantitative part of the BN is formed by the conditional probability tables (CPT), which are assigned to each node. In each CPT, the defined states of the considered node are assigned for each possible state combination (Russel et al., 2010). The creation of BN is done in the following three steps as discussed by Ansari et al. (2020): (1) creation of an Object-oriented Bayesian Network, (2) building a static BN, (3) Incorporating temporal component for deriving dynamic BN (DBN) from the BN. This makes it possible to map the relationships of the variables over time. DBN are dynamic models, which allow what-if analysis and reasoning over time, considering the evolution of variables and temporal distributions of discrete time points i in the interval $0 \leq i \leq T$ (Ansari et al., 2020). DBN can be constructed manually with the help of domain experts who build the network and assign CPT. However, DBN can also be learned automatically, but this requires the use of special algorithms such as the Expectation Maximization (EM), General Expectation Maximization (GEM) algorithm (Mihajlovic & Petkovic, 2001), or Markov Chain Monte Carlo (MCMC) models (Liang et al., 2020). Ansari et al. (2020) see DBN as ideal models for the necessary predictive capabilities of SCM and industrial maintenance in particular.

Hosseini and Ivanov (2019) studied the OEM (Original Equipment Manufacturer) exposure to the disruption propagation of its supply networks, where they developed a function for assessing the vulnerability and recoverability using BN. This enabled to measure the resilience of the SC of OEMs in the aerospace and automobile industry. BN can be used in combination with FMEA for risk analysis (Rastayesh et al., 2020) of the power conditions in polymer electrolyte membrane fuel cells. Kulkarni et al. (2021) integrated FMEA into BN in order to enable health monitoring and increase the reliability of critical infrastructure in the aerospace industry. To tackle the increased scale and complexity in software intensive manufacturing systems Yang et al. (2018) developed a framework, based on case-based reasoning, FMEA and BN for dynamic multi-fault diagnosis, considering uncertainty, in the aerospace industry. Further in the aerospace industry, Li et al. (2017) developed a DBN for health monitoring of airframes for the prediction of crack growth. A generic DBN-enhanced methodology of improving KPIs, especially RAMS for OEMs and machine users along product lifecycle was introduced by Passath et al. (2021). To combine pre- and post-failure phases in risk assessments, a DBN was developed by Tong et al. (2020) in order to increase resilience. The developed methodology was then applied to historical data from refinery accidents in order to demonstrate the applicability.

DBNs can be categorized into two groups stationary and non-stationary DBNs. Stationary DBNs do not consider the evolving nature of edges over time, whereas non-stationary DBNs (nsDBN) allow the use of a temporal dimension and simultaneously considering uncertainty (Ansari et al., 2020). nsDBNs need to learn conditional dependencies from complex multivariant time-series data. Thus, new learning approaches should be used. Hourbracq et al. (2016) propose an algorithm that decides at each time step, based on the likelihood in a data stream and a sliding window, whether to use an already known model or a new one for the prediction. The starting point of the algorithm is a given, initial network. Furthermore, nsDBN can currently handle abrupt, but not gradual, concept drift well. Meng et al. (2019) present a learning algorithm that addresses this problem and continuously updates the network through a logical search and global optimization. This enables various applications of nsDBN. Serras et al. (2021) designed the ETEOR method for outlier detection in multivariate time series and validated the approach using data from electrocardiogram alert systems, historical data compromising male mortality in France and pen-digit recognition. Quesada et al. (2021) developed a trend forecasting algorithm using DBN in non-stationary time series for industrial furnaces. nsDBNs were used by Zhang et al. (2021) for dynamic risk analysis in tunnel construction processes for non-stationary time-series recognition. The application of nsDBN in the area of maintenance of highly flexible production systems was proposed by Ansari et al. (2020). This would enable the unification of Event-Cost Schema with the temporal dimension of cause-effect analysis (cf. Fig. 8.1). In the context of maintenance, multi-channels of data sources are involved in the creation of nsDBN, as shown in Fig. 8.1. The results from object-oriented analyses such as the FMEA analysis are particularly worth mentioning here. Therefore, systems, subsystems, related components, and their possible fault conditions are analyzed. The results of

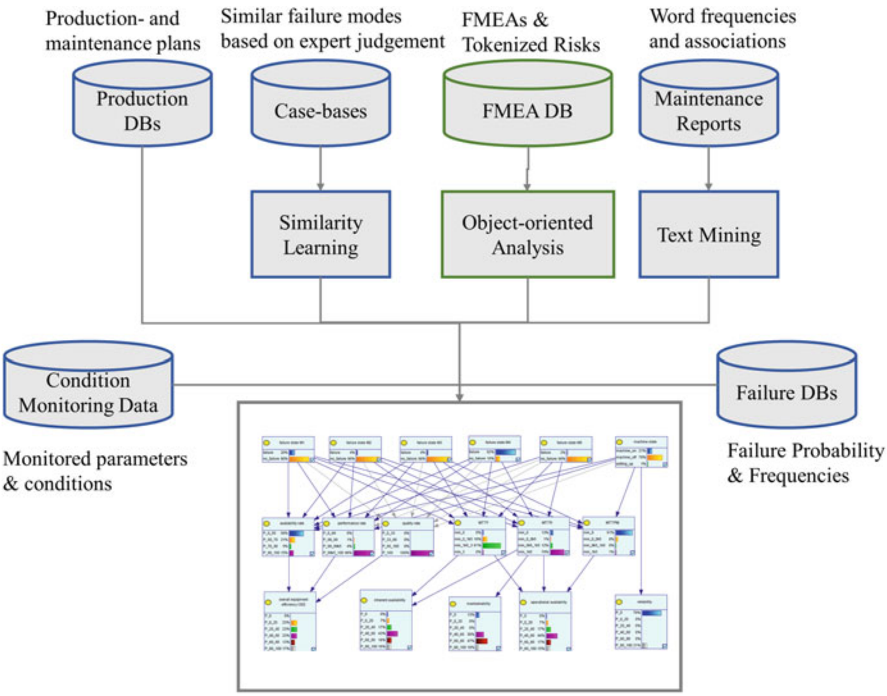


Fig. 8.1 Possible data sources for DBN in a resilient SC

these analyses represent the tokenized risks for the creation of the network. The statistical probabilities for these risks can be taken from fault databases. In turn, the expert knowledge expressed in form of troubleshooting reports and maintenance documentations can be analyzed and reflected opinions, recommendations, and measures for handling problems can be extracted using AI-enhanced approaches presented by Ansari et al. (2021). Furthermore, expert knowledge formalized as cases including solutions for solving previous problems (Riester et al., 2020) can be analyzed with the help of similarity learning algorithms to enrich the nsDBN. In order to map the temporal and changeable components in nsDBN, real-time data is needed to enable the constant evolution of the networks. This includes condition monitoring data and data from production and maintenance systems including maintenance and production plans and schedules as well as failure databases.

Considering the above discussion, the advantages and disadvantages of DBN should be considered as well (McCloskey, 2000). The major disadvantage of DBN is that there is no universal way to create them and that the creation requires a very high resource investment. Since a DBN also uses causal relationships, which are based on the knowledge of the experts involved, a DBN is also limited in this respect. However, these disadvantages are also the advantages of DBN, since new knowledge can easily be incorporated. Probably the biggest advantage of DBN is its ability to reason in two directions and that the result is explicit, unlike in other

Table 8.1 Classification of the results of the literature analysis of the application of BN

Paper	Application area	Application domain	Type of BN
Ansari et al. (2020)	Manufacturing	Maintenance planning	nsDBN
Hosseini and Ivanov (2019)	Aerospace & automobile Industry	Risk analysis	DBN
Hourbracq et al. (2016)	Simulated data	Algorithm design	nsDBN
Kulkarni et al. (2021)	Aerospace Industry	Health monitoring	DBN
Li et al. (2017)	Aerospace Industry	Health monitoring	DBN
Meng et al. (2019)	Simulated data	Algorithm design	nsDBN
Passath et al. (2021)	Manufacturing	Maintenance planning	DBN
Quesada et al. (2021)	Manufacturing	Trend forecasting	DBN
Rastayesh et al. (2020)	Energy Sector	Risk assessments	DBN
Schenkelberg et al. (2020a)	Manufacturing	Maintenance planning	DBN
Tong et al. (2020)	Energy Sector	Risk assessments	DBN
Yang et al. (2018)	Aerospace Industry	fault diagnosis	DBN
Zhang et al. (2021)	Construction	Risk analysis	nsDBN

Machine Learning techniques such as Neural Networks. The probability, as a DBN output, can be interpreted in a deterministic way as KPIs by defining a threshold. This is in fact the main advantage of integrative modeling and analysis of multiple KPIs and their interrelations for building resilience in manufacturing and SCs.

The results presented can also be discussed qualitatively as shown in Table 8.1. It can be clearly seen that DBN is mainly used in the field of manufacturing. The aircraft industry is particularly strong in this respect, where the advantages of BN are clearly evident. The publications also show that nsDBNs have only been used in practical industrial examples in recent years. Sectors such as energy and maintenance also benefit from BN, especially DBN and nsDBN.

8.3 Application of Dynamic Bayesian Network in Industrial Maintenance

The characteristics and applications of DBN identified in the literature analysis can be illustrated using a practical example from industrial maintenance in the consumer goods industry. The production process is divided into four sub-processes: (1) in the filling step the product is filled into the empty containers. The incorrectly filled containers are sorted out by means of a weight check. In the stage of (2) packaging, the carton is erected, the filled container with consumables is placed inside and sealed. Then the label is applied to the packaging. The filled production cartons are then (3) placed in a display carton. The display cartons are then (4) packed into transport cartons. In the following example, the packing process (2) of the containers into the product carton is examined. This process can again be broken down into sub-processes. In the production plant, the machine states and the individual feeder

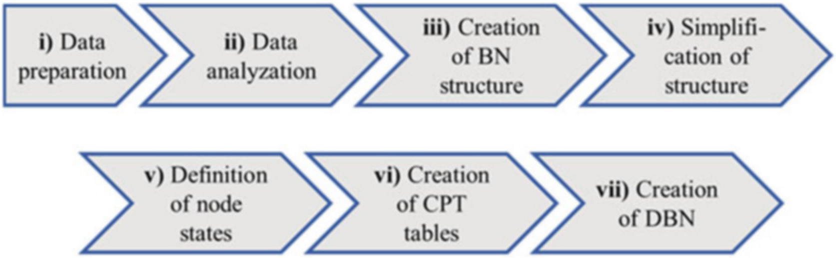


Fig. 8.2 Implementation process of the DBN in an application from the consumer goods industry

states of the process steps are automatically recorded in a database consisting of a table called history list. In addition, the piece counters are recorded before the start of the packaging process. This is done via the weight check. Defective products are rejected in the process. Machine breakdowns often lead to long downtimes in these highly automated systems. For this reason, a preventive maintenance strategy is currently being pursued. However, this ties up many highly specialized maintenance technicians. Particularly in the wake of the COVID-19 pandemic, this is leading to staff shortages. A maintenance strategy that only requires the situational deployment of personnel would lead to a strengthening of resilience in manufacturing and SC. The DBN model presented in the following section provides clear guidelines for the introduction of a predictive maintenance strategy in the use case described.

The modeling of the DBN is based on the process shown in Fig. 8.2. The approach is an adopted version of the approach presented by (Ansari et al., 2020). This is due to the fact that all necessary data exists in a database, where the rows represent the objects of an Object-oriented Bayesian Network. The starting point here is the history list table, which in a first step must be (1) prepared and then (2) analyzed. Furthermore, the DBN is created manually. This starts with the (3) creation of the structure which is then (4) simplified. After that, the (5) states of the nodes are determined and these are filled with (6) CPT tables. This allows consequently the (7) generation of a DBN from the BN by adding a temporal component.

8.3.1 Data Preparation and Analysis

During the process, both the change in the machine state and the occurrence of a fault state are listed and stored in a so-called history list. The data of the history list is analyzed in order to be able to use it profitably for the BN. In the history list, machine states, fault states and piece count records are listed in equal measure. The Value ID determines whether the lines in the history list are a machine or fault state or a piece count record. The Value ID thus enables a distinction to be made between the types machine status, fault status and piece count recording. However, based

Table 8.2 Excerpt from the history list

ID	Dt_data	Entry ID	Flags	Machine ID	Value ID	Value	Client IP
96944	31.07.2017 09:13:22	0	1	103	200	0	91.141.1.138

Table 8.3 Excerpt from the list of machine states

ID	Dt_data	State ID	Client IP	Machine state	Client IP	Duration [min]
96943	31.07.2017 09:08:14	103-200-16	91.141.1.138	Setup	31.07.2017	5.1
96944	31.07.2017 09:13:22	103-200-0	91.141.1.138	Activated	31.07.2017	180.7
97327	31.07.2017 12:14:09	103-200-16	77.119.130.153	Setup	31.07.2017	4.4

Table 8.4 Excerpt from the list of failure conditions

ID	Dt_data	State ID	Machine state	Client IP	Duration [min]
97883	01.08.2017 07:13:13	103-211-128	Time out cylinder product slide at the outlet	01.08.2017	0.03
97884	01.08.2017 07:13:15	103-211-0	No fault active at M2!	01.08.2017	0.42
97885	01.08.2017 07:13:40	103-211-1024	Machine encoder zero setting—Manual cycle	01.08.2017	0.03

on the Value ID, no statement can be made as to which machine or fault status is involved. The lines of the history list should be clearly assigned to the machine and fault states. A primary key is required for a unique assignment. For this purpose, one line of the history list is used as an example, see Table 8.2.

The columns Machine ID, Value ID and Value are subsequently combined to form the primary key State ID to ensure unique identification of the machine and fault states (e.g., 103-200-16). With the help of experts, the fault states are assigned to five different categories with the state IDs 103-210-X (category M1) to 103-214-X (category M5). A fault condition of the respective category is considered to be eliminated when the associated Value 0 appears. In order to be able to determine the duration of a fault condition that has occurred, the faults must be separated and differentiated in their five categories M1 to M5, since a fault of a different category can occur between the fault event message and the fault correction message (Table 8.3).

Three machine states can occur during the process, namely (1) Machine activated, (2) Machine off, and (3) Setup process. A machine state is active until it is replaced by another machine state. Subsequently, for each machine status, the total duration, the number of appearances and the average duration per appearance are determined (Table 8.4).

The fault states are assigned to the five different categories with the state IDs 103-210-X through 103-214-X. A fault condition of the respective category is considered to be eliminated when the associated condition ID 103-21X-0 appears in further sequence, the total duration, the number of appearances and the duration per appearance are determined for each fault condition.

8.3.2 Manual Modeling of the Dynamic Bayesian Network

The manual modeling of the BN is conducted in several steps. First, the nodes of the model are determined and classified into the different levels of the model. Then, the connections of the nodes are created using arrows, which represent the causal relationships of the nodes. By visualizing the dependencies of the nodes, it also becomes clear which nodes are not crucial for the validity of the model. These are eliminated in the further consequence. In order to complete the model, the probability tables of the individual nodes are populated with their conditional probability values. Subsequently, a temporal component is introduced to make the BN dynamic and thus to model a DBN. In order to generate the model, the nodes must first be determined. The goal of this use case is the modeling of a DBN for the reliable prediction of predictive maintenance and simulation for introducing a predictive maintenance strategy with the help of KPIs to increase the resilience of the production process. For the DBN, maintenance relevant KPIs of the management level are required, which describe the maintenance characteristics of the production process. For the creation of the BN, data of the production process from the evaluated database of the history list, which originates from the operational level, is used. This data consists of the machine status, the fault status, and the production quantities at the time in question. The fault statuses are thereby separated into five categories.

A connection between the nodes based on the process data (operational level) and the nodes of the KPIs (management level) should be created with the help of nodes on an intermediate level, see Fig. 8.3. The required node points thus also function as a link between the operational level and the management level. In addition, the wanted nodes (effect) result from the nodes of the process data (cause), but at the same time, they themselves represent a cause for the nodes of the KPIs (effect). The nodes of the intermediate level result from the formulas for the calculation of the performance indicators. The nodes from which the arrow originates (shaft of the arrow) are called parent nodes of the nodes in which the arrow ends (arrowhead). In order to create a certain overview, the causal relationships are presented in Table 8.5.

The introduced causal relationships illustrate the fact that some introduced nodes have no meaning for the prediction of maintenance properties, see Table 8.5. These facts result in a simplified model that forms the basis for the BN, see Fig. 8.4. In the BN, maintenance-relevant KPIs are used as the basis of the model. The formation of the individual nodes is designed in such a way that the nodes within a level (operational level, intermediate level, and management level) already correspond to the assignment to the individual KPI types. Subsequently, the levels are named

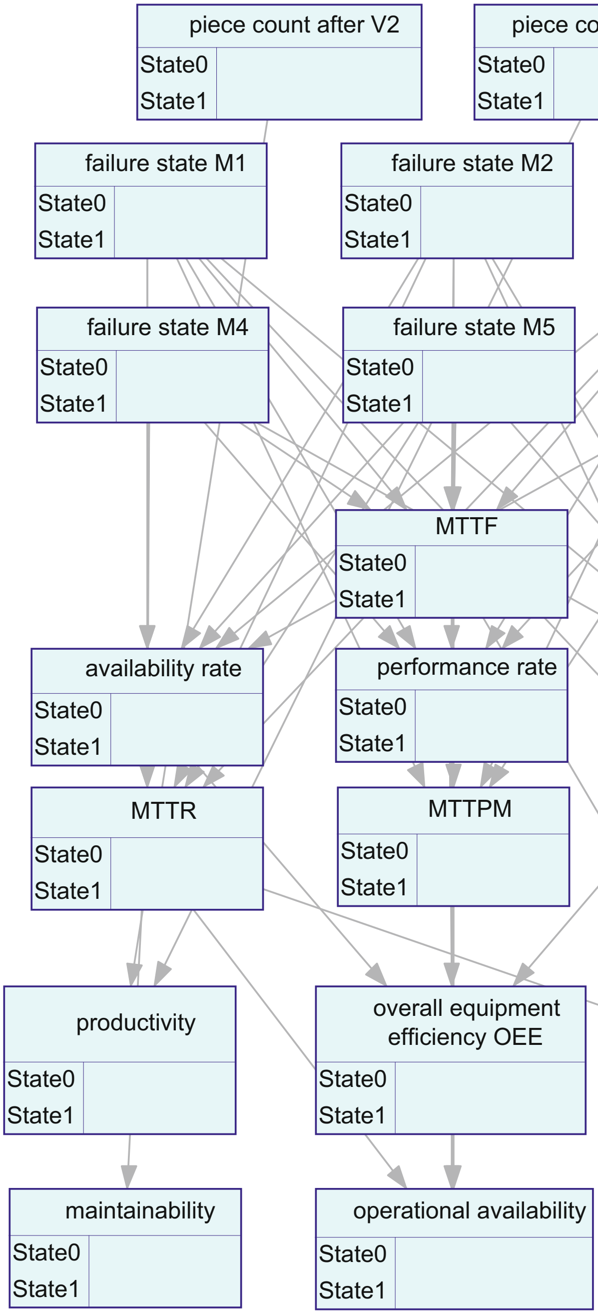


Fig. 8.3 Nodes of the intermediate level with their causal relations

Table 8.5 Causal relationships between nodes

Node (effect)	Parent node (cause)				
Productivity	Quantity before process (2)	Quantity after process (2)			
OEE	Utilization rate	Performance grade	Quality grade		
Availability	MTTF	MTTR			
Maintainability	MTTR				
Operational availability	MTTF	MTTR	MTTPM	MDT	SDT
Reliability	Machine state				

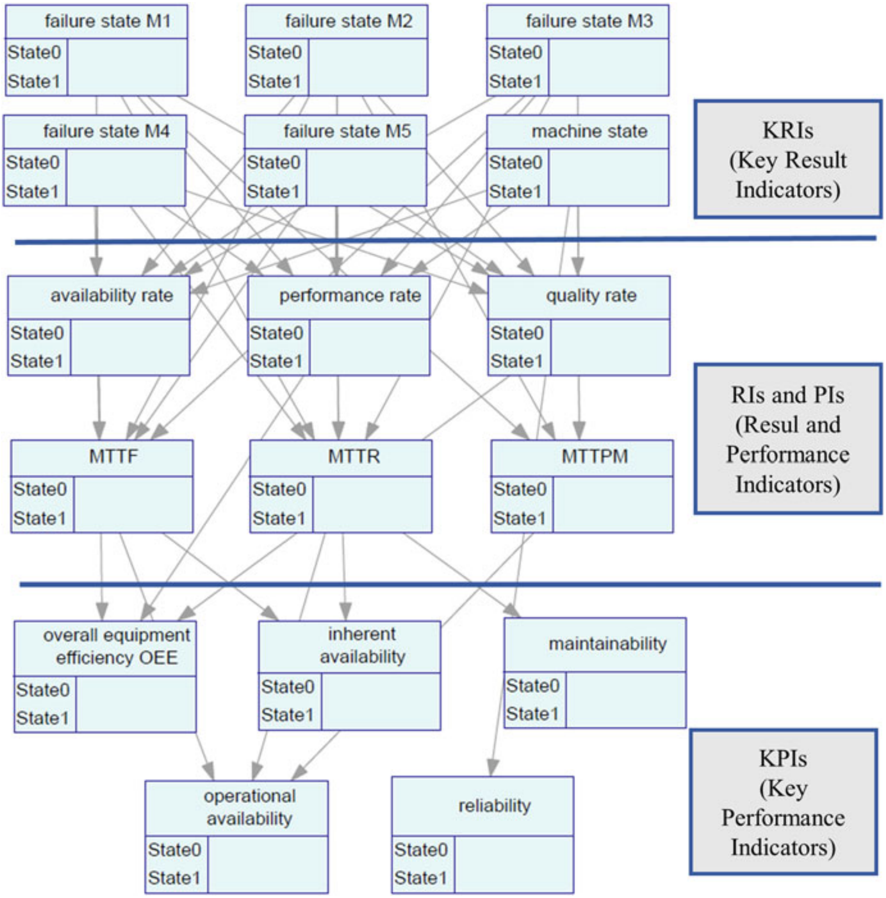


Fig. 8.4 Simplified model as the basis for the BN, with KPIs as model levels

Table 8.6 Possible states of nodes in the BN

Node	State	Description
Failure state M1–M5	Fault	A fault occurs
	No fault	No fault occurs
Machine status	Machine active	
	Machine not active	
	Setup process	
Degree of utilization, Degree of performance, Quality grade	P_0_98	0–98% Performancep
	P_98_99	98.001–99% Performance
	P_99_99k5	99.001–99.5% Performance
	P_99k5_100	99.501–100% Performance
MTTR, MTTF, MTTPM	Min_0	0 min MTTR
	Min_0_0k5	0–0.5 min MTTR
	Min_0k5_1k5	0.501–1.5 min MTTR
	Min_1k5	More than 1.5 min MTTR
OEE, Internal and operational availability, Maintainability, Reliability	P_0	0%P
	P_0_20	0.001–20%
	P_20_40	40.001–60%
	P_40_60	40.001–60%
	P_60_80	60.001–80%
	P_80_100	80.001–100%

according to the key figure types. The naming of the levels is therefore Key Result Indicator (KRI) level, Result Indicator/Performance Indicator (RI/PI) level and KPI level.

Each node can have two or more states. The number of columns, and states, of the CPT of a node is given by the number of states of the parent nodes. The number of states is defined by the column count of the nodes, see Eq. (8.1). After determining the states, the cells of the CPT of each node are filled with the corresponding values. The states of the individual nodes are described in Table 8.6.

Calculation of the number of states per node as follows:

$$\text{Number of States per Node} = \prod \text{States of the Parent Nodes} \tag{8.1}$$

8.3.3 *Probability Values of KRIs*

First, the probability values for the states of the fault status nodes (cf. Table 8.6) and the machine status node should be determined. The probability values of the individual machine states are entered in the CPT of the machine status node. The probability that a certain machine state exists is expressed by the relative duration of this state. This is obtained by dividing the total duration of the machine state under consideration with the sum of the total durations of all states. Each fault status category (M1–M5) gets its own fault status node. The possible states of the fault status nodes are reduced to two (“fault” or “no fault”), because if all fault states are taken into account, the CPT of the subsequent nodes would be reduced to a size that would no longer justify the workload. The second variant limits the number of states of the individual fault status nodes to two. If all fault states were considered, there would be 3,779,136 nodes; by limiting them to two fault states, only 96 nodes need to be modeled. To obtain the column count of the CPT, the number of possible states of each parent node is multiplied by each other. The probability of having a particular fault state is expressed by the relative total duration of that state. This is obtained by dividing the total duration of the considered fault state with the sum of the total duration of all states.

8.3.4 Determination of the Probability Values of the RIs and PIs

The fault and machine status nodes at the KRI level are parent nodes of the RIs and PIs, respectively, and feed directly into the calculation of the probability values of the RIs and PIs. The KRIs can thus be seen as the cause on the effect of the nodes from the RI/PI level. For the calculation of the probability values in the RI/PI level, machine or fault statuses are classified according to their properties. These properties can be taken from the analysis of the machine and fault states. A distinction is made between preventive maintenance or repair. For the calculation of the machine or fault states the equipment time is to be considered. The distinction between preventive maintenance and repair must be taken into account when calculating Mean Time To Repair (MTTR) and Mean Time To Preventive Maintenance (MTTPM). While a condition that is relevant for an MTTR calculation results in a repair activity, the MTTPM-relevant conditions cause a preventive maintenance activity. For the calculation of the utilization, performance, and quality grade probabilities of importance, resource states are required. To be able to calculate the RIs and PIs of the individual state combinations, the mean value of the failure-free time of the failure state categories is determined. In order to determine the probability of the states of the node points in the next step, the probabilities for the occurrence of the individual state conditions are calculated. These are calculated from the product of the probabilities of the parent nodes. The CPT of the considered node are multiplied by the corresponding values of the probability of the state combination. This gives the probability of a state of the node for a considered state combination. Modern programs for modeling BNs such as GeNIe SMILE automatically compute the probabilities of the states of the nodes using the distribution function of the BN.

8.3.5 Determination of the Probability Values of the KPIs

The nodes of the RI/PI level are parent nodes of the KPI nodes and are directly involved in the calculation of the probability values of the KPIs. The RI/PI nodes can thus be seen as the cause on the effect of the nodes from the KPI level. In the following, the filling of the CPT cells of the nodes is explained. The number of columns of the matrix is given by the number of possible state combinations of the parent nodes. To fill the CPT of the node, the minimum and maximum values of the node are calculated for each state combination of the parent nodes. For filling the CPT, the calculated minimum and maximum values are considered. These two values yield a range in which the actual value of the node for the considered state combination will lie. It is necessary to classify this range into the states of the node. If a state of the node contains a subset of the range of the node, the share of this subset is considered in the CPT. The calculated values of the CPT are entered into the CPT of the node points. Modern programs for modeling BNs, such as GeNIe SMILE, automatically calculate the probabilities of the states of the nodal points with the help of the distribution function of the BN. For the probabilities of the states of the node points, the probability for the occurrence of the individual state combinations is required. The probability of the state combination is calculated from the product of the probabilities of the parent nodes for their considered states.

8.3.6 Manual Modeling of the DBN

The created BN is a snapshot of the system at a given time and is used to model systems that are in an equilibrium state. However, in reality, systems change over time and it is consequently of great interest to see how these systems evolve over time. Therefore, a model capable of modeling a dynamic system is needed. The use of DBN allows the extension of the BN with a temporal component. In doing so, the network structure or its parameters do not change. The underlying process is thus stationary. However, the system becomes dynamic. To form a DBN from the manually created BN, a number of time steps t are assigned to the nodes. In GeNIe SMILE, this is done by moving the nodes into the so-called Temporal Plate. It is important to note that all nodes must be moved into the area at the same time, otherwise the causal relationships will not be converted correctly. In the present model, the nodes of the KRI level influence themselves over the time intervals. This can be illustrated by an example.

If no fault occurs at fault status M1 in the past time interval, the probabilities of fault status M1 remain identical for the considered time interval in the CPT. If a fault message appears at fault status M1 in the previous time interval, the probabilities of fault status M1 in its CPT are different from those in the intervals before. Therefore, it is necessary to consider the state of the previous time interval. For each node of the KRI level, a temporal link (arrow) to itself is needed. The result of the previous steps is the DBN as seen in Fig. 8.5. For the creation of a model that corresponds

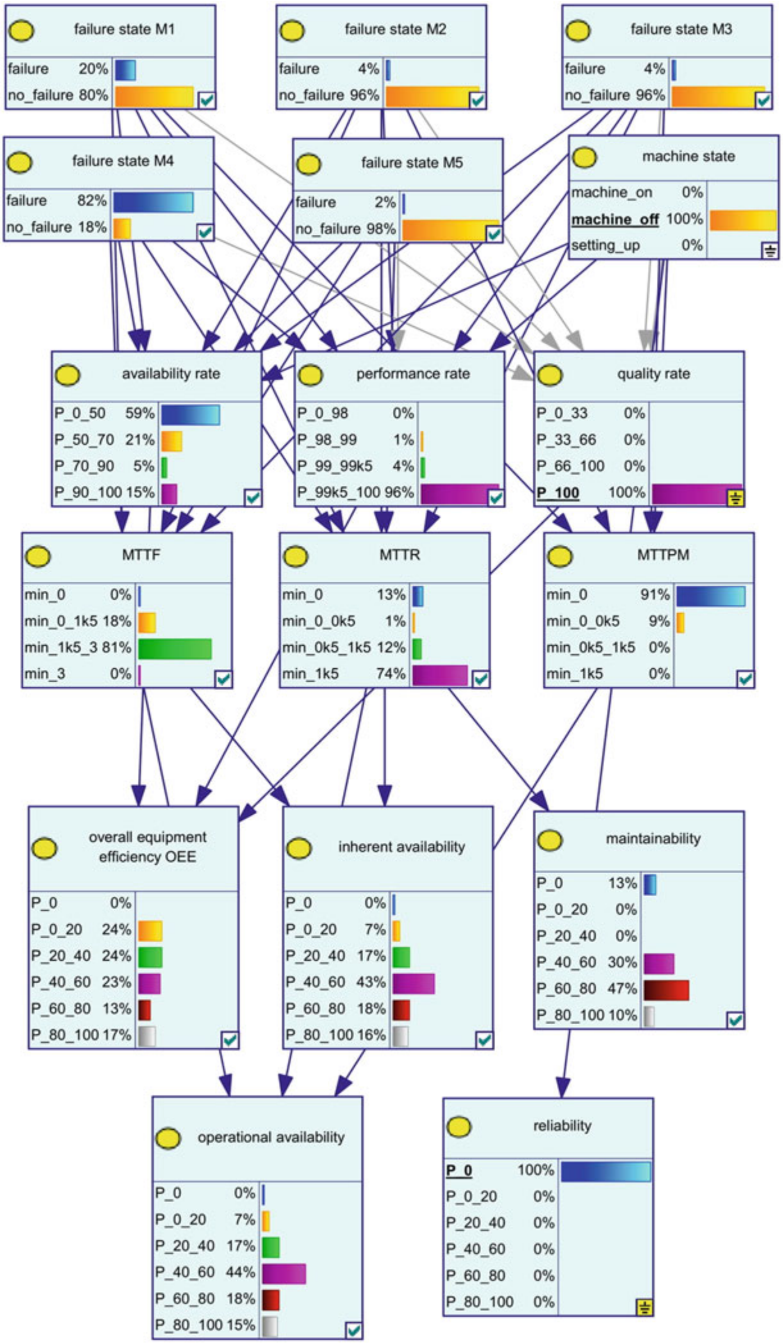


Fig. 8.5 The resulting DBN describing the production process

to the real production process, expert knowledge for the method and the process is needed. This ensures that the prediction generated by the model will be true in the future.

8.4 Discussion of Results

The effort for data preparation is considerable for the manual creation of a DBN, because first the database has to be processed and then machine and fault states have to be analyzed in order to calculate the corresponding KPIs. Subsequently, the CPTs of the individual nodes are calculated. The calculation of the ratios (RI/PIs and KPIs) and the subsequent calculation of the CPTs of the nodes represent the time-consuming work of data preparation. The manual creation of the BN with the modeling of the nodes and the creation of the causal relationships, as well as the filling of the CPTs is also very time-intensive. However, the information content is significantly higher than with automatically created DBN. Since exact calculations and no approximations form the basis and the modeled relationships were created with application experts. This allows the DBN to display exactly the information (e.g., KPIs) required by the user. The robustness, adaptability, and therefore resilience of the network created with experts is also significantly higher than that of automatically created networks. A DBN allows production and SC managers to plan their processes. The model thus provides clear recommendations, based on visualization of the network and KPIs' interrelations, on how, for example, availability can be increased and what the corresponding KRIs for this purpose must look like. A DBN also helps on the operational level because it can show through the use of KPIs how failure states can be reduced in general or in particular case. This enables the choice of the right maintenance strategy, as DBNs allow its evaluation before implementation. The deteriorating condition of the components over time is also taken into account. This is an important advantage, especially when estimating maintenance costs. DBN enable the transition from a preventive maintenance strategy to a predictive maintenance approach. This avoids unplanned downtime as far as possible and thus not only increases productivity but also optimizes product quality, effectiveness, resilience viability of the production process.

In practical terms, the potential for improvements by DBN can be illustrated using the use case from the consumer goods industry. By using the DBN, a specific machine down event was reduced by 30%. The benefits of the implemented DBN can also be seen in the entire use case, where an improvement in overall availability of 9% has been achieved.

8.5 Outlook

DBN should be adapted with the help of expert knowledge in order to represent reality, as optimal as possible and thus ensure a reliable forecast of maintenance KPIs, or disruption and changes along SCs. The DBN model presented in this chapter is based on a stationary production process. The limitations of a stationary model are that the defined connections cannot change over time. This does not necessarily reflect the reality of the process. Changes in the relations occur is due to increasing market volatility, which is mainly characterized by customer demand fluctuations, but also changes in the SC. Due to these uncertainties, a higher flexibility in the production process is needed. This is realized by a non-stationary production process. Non-stationary processes can be found not only in production, but also in social networks, in reconfigurable construction as well as in SC. All these examples have in common that elements in these networks are interconnected, their relationships change over time, and also that the relationships themselves are not stationary. These characteristics can be modeled by nsDBN. Hence, it can be concluded that nsDBNs enable new possibilities in planning, monitoring, and controlling in production SC and therefore ultimately strengthen resilience in SC.

Besides, the future research agenda should reinforce the use of DBNs by means of multi-channel data pipelines. This will be driven in particular by the use of new trends in the field of AI. The application of federated learning (FL) enables the use of assistance systems in manufacturing and logistics even in the event of IT and infrastructure breakdowns. At the same time, these assistance systems can be used in privacy-sensitive areas on heterogeneous hardware. The combination of such FL approaches with further AI models to a cognitive maintenance system for decision support was presented in Kohl et al. (2021). The presented approach supports the resilience viability of the SC by the possibility to react flexibly and proactively to events.

References

acatech. (2014). *Resilien-Tech; "Resilience by Design": A strategy for the technology issues of the future*. acatech – NATIONAL ACADEMY OF SCIENCE AND ENGINEERING. Accessed August 04, 2021, from https://www.acatech.de/projekt/resilien-tech-resilience-by-design-strategie-fuer-die-technologischen-zukunftsthemen/

Ansari, F., Khobreh, M., Seidenberg, U., & Sihn, W. (2018). A problem-solving ontology for human-centered cyber physical production systems. *CIRP Journal of Manufacturing Science and Technology, 22C*, 91–106.

Ansari, F., Glawar, R., & Nemeth, T. (2019). PriMa: A prescriptive maintenance model for cyber-physical production systems. *International Journal of Computer Integrated Manufacturing, 32*(4–5), 482–503.

Ansari, F., Glawar, R., & Sihn, W. (2020). Prescriptive maintenance of CPPS by integrating multimodal data with dynamic Bayesian networks. In J. Beyerer, A. Maier, & O. Niggemann (Eds.), *Machine learning for cyber physical systems* (pp. 1–8). Springer.

Ansari, A., Kohl, L., Giner, J., & Meier, H. (2021). Text mining for AI enhanced failure detection and availability optimization in production systems. *CIRP Annals – Manufacturing Technology, 40*(1), 373–376.

Bai, J., Chang, X., Trivedi, K. S., & Han, Z. (2021). Resilience-driven quantitative analysis of vehicle platooning service. *IEEE Transactions on Vehicular Technology, 70*, 5378–5389. https://doi.org/10.1109/TVT.2021.3077118

Bauer, D., Böhm, M., Bauernhansl, T., & Sauer, A. (2021). Increased resilience for manufacturing systems in supply networks through data-based turbulence mitigation. *Production Engineering and Research Development, 15*, 385–395. https://doi.org/10.1007/s11740-021-01036-4

Bhatia, G., Lane, C., & Wain, A. (2013). *Building resilience in supply chains; An initiative of the risk response network*. World Economic Forum. Accessed August 03, 2021, from http://www3.weforum.org/docs/WEF_RRN_MO_BuildingResilienceSupplyChains_Report_2013.pdf

Bonde, H. (2018). *3 examples of reducing supply chain uncertainty – downstream*. SAS. Accessed August 03, 2021, from https://blogs.sas.com/content/hiddeninsights/2018/07/12/reducing-supply-chain-uncertainty-downstream/

Capgemini. (2020) *Fast forward: Rethinking supply chain resilience for a post-COVID-19 world*. Capgemini Research Institute. Accessed August 04, 2021, from https://www.capgemini.com/wp-content/uploads/2020/11/Fast-forward_Report.pdf

Chen, X., Xi, Z., & Jing, P. (2017). A unified framework for evaluating supply chain reliability and resilience. *IEEE Transactions on Reliability, 66*, 1144–1156. https://doi.org/10.1109/TR.2017.2737822

Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management, 15*, 1–14. https://doi.org/10.1108/09574090410700275

Esmaeel, R. I., Zakuan, N., Jamal, N. M., & Taherdoost, H. (2018). Understanding of business performance from the perspective of manufacturing strategies: Fit manufacturing and overall equipment effectiveness. *Procedia Manufacturing, 22*, 998–1006. https://doi.org/10.1016/j.promfg.2018.03.142

Giebler, C., Gröger, C., Hoos, E., Eichler, R., Schwarz, H., & Mitschang, B. (2020). Data Lakes auf den Grund gegangen. *Datenbank-Spektrum, 20*, 57–69. https://doi.org/10.1007/s13222-020-00332-0

Golan, M. S., Jernegan, L. H., & Linkov, I. (2020). Trends and applications of resilience analytics in supply chain modeling: Systematic literature review in the context of the COVID-19 pandemic. *Environment Systems and Decisions, 40*, 222–243. https://doi.org/10.1007/s10669-020-09777-w

Hosseini, S., & Ivanov, D. (2019). A new resilience measure for supply networks with the ripple effect considerations: A Bayesian network approach. *Annals of Operations Research*. https://doi.org/10.1007/s10479-019-03350-8

Hourbracq, M., Wuillemin, P. H., Gonzales, C., & Baumard, P. (2016). Real time learning of non-stationary processes with dynamic Bayesian networks. In *Information processing and management of uncertainty in knowledge-based systems* (pp. 338–350). Springer. https://doi.org/10.1007/978-3-319-40596-4_29

Ivanov, D. (2020). Viable supply chain model: Integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the COVID-19 pandemic. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03640-6

Ivanov, D., & Dolgui, A. (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control, 32*(9), 775–788. https://doi.org/10.1080/09537287.2020.1768450

Ivanov, D., Sokolov, B., Chen, W., Dolgui, A., Werner, F., & Potryasaev, S. (2021a). A control approach to scheduling flexibly configurable jobs with dynamic structural-logical constraints. *IISE Transactions, 53*(1), 21–38. https://doi.org/10.1080/24725854.2020.1739787

Ivanov, D., Blackhurst, J., & Das, A. (2021b). Supply chain resilience and its interplay with digital technologies: Making innovations work in emergency situations. *International Journal of Physical Distribution and Logistics Management, 51*(2), 97–103. https://doi.org/10.1108/IJPDLM-03-2021-409

Ivanov, D. (2022). Digital supply chain management and technology to enhance resilience by building and using end-to-end visibility during the COVID-19 pandemic. *IEEE Transactions on Engineering Management*, 1–11. https://doi.org/10.1109/tem.2021.3095193

Karl, A. A., Micheluzzi, J., Leite, L. R., & Pereira, C. R. (2018). Supply chain resilience and key performance indicators: A systematic literature review. *Production, 28*. https://doi.org/10.1590/0103-6513.20180020

Klappich, D., & Muynck, B. (2020). *Predicts 2021: Supply chain technology*. Gartner. Accessed August 03, 2021, from https://www.gartner.com/en/documents/3993865/predicts-2021-supply-chain-technology

Knight, F. H. (2014). *Risk, uncertainty and profit*. Martino Publishing.

Kohl, L., Ansari, F., & Sihn, W. (2021). *A modular federated learning architecture for integration of AI-enhanced assistance in industrial maintenance*. Academic Society for Work and Industrial Organization. (in Press).

Kulkarni, C. S., Corbetta, M., & Robinson, E. I. (2021). *Systems health monitoring: Integrating FMEA into Bayesian Networks 2021 IEEE Aerospace Conference (50100)* (pp. 1–11). IEEE.

Li, C., Mahadevan, S., Ling, Y., Choze, S., & Wang, L. (2017). Dynamic Bayesian network for aircraft wing health monitoring digital twin. *AIAA Journal, 55*, 930–941. https://doi.org/10.2514/1.J055201

Liang, H., Ganeshbabu, U., & Thorne, T. (2020). A dynamic Bayesian network approach for analysing topic-sentiment evolution. *IEEE Access, 8*, 54164–54174. https://doi.org/10.1109/ACCESS.2020.2979012

McCloskey, S. (2000). Probabilistic reasoning and Bayesian networks. In *Proceedings of Neural Networks and Machine Learning (ICSG).*

Meng, Q., Wang, Y., An, J., Wang, Z., Zhang, B., & Liu, L. (2019). Learning non-stationary dynamic Bayesian network structure from data stream. In *2019 IEEE Fourth International Conference on Data Science in Cyberspace (DSC)* (pp. 128–134). IEEE.

Mihajlovic, V., & Petkovic, M. (2001). *Dynamic Bayesian networks: A state of the art*. University of Twente Document Repository.

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., … Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals, 65*(2), 621–641.

Panetto, H., Iung, B., Ivanov, D., Weichhart, G., & Wang, X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control, 47*, 200–213. https://doi.org/10.1016/j.arcontrol.2019.02.002

Passath, T., Huber, C., Kohl, L., Biedermann, H., & Ansari, F. (2021). A knowledge-based digital lifecycle-oriented asset optimisation. *Tehnički glasnik (Online), 15*, 226–334. https://doi.org/10.31803/tg-20210504111400

Quesada, D., Valverde, G., Larrañaga, P., & Bielza, C. (2021). Long-term forecasting of multivariate time series in industrial furnaces with dynamic Gaussian Bayesian networks. *Engineering Applications of Artificial Intelligence, 103*, 104301. https://doi.org/10.1016/j.engappai.2021.104301

Rastayesh, S., Bahrebar, S., Blaabjerg, F., Zhou, D., Wang, H., & Dalsgaard Sørensen, J. (2020). A system engineering approach using FMEA and Bayesian network for risk analysis—A case study. *Sustainability, 12*, 77. https://doi.org/10.3390/su12010077

Riester, R., Ansari, A., Foerster, M., & Matyas, K. (2020). *A procedural model for utilizing case-based reasoning in after-sales management*. 18th International Scientific Conference on Industrial Systems – Industrial Innovation in Digital Age, October 7–9, 2020, Novi Sad, Serbia.

Rölli, M. (2021). Der Supply Chain Control Tower zur Steuerung des Transport-Managements. *Wirtsch Inform Manag, 13*, 20–29. https://doi.org/10.1365/s35764-020-00313-8

Schenkelberg, K., Seidenberg, U., & Ansari, F. (2020a). Analyzing the impact of maintenance on profitability using dynamic Bayesian networks. *13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Procedia CIRP, 88*, 42–47.

Schenkelberg, K., Seidenberg, U., & Ansari, F. (2020b). Supervised machine learning for knowledge-based analysis of maintenance impact on profitability, 21st IFAC World Congress, July 12–17, 2020, Berlin. *IFAC-PapersOnLine, 53*(2), 10651–10657.

Schenkelberg, K., Seidenberg, U., & Ansari, F. (2020c). A simulation-based process model for analyzing impact of maintenance on profitability. In *25th IEEE International Conference on Emerging Technologies and Factory Automation (IEEE ETFA), September 8–11, Vienna* (pp. 805–812).

Scholten, K., Stevenson, M., & van Donk, D. P. (2020). Dealing with the unpredictable: Supply chain resilience. *IJOPM, 40*, 1–10. https://doi.org/10.1108/IJOPM-01-2020-789

Serras, J. L., Vinga, S., & Carvalho, A. M. (2021). Outlier detection for multivariate time series using dynamic Bayesian networks. *Applied Sciences, 11*, 1955. https://doi.org/10.3390/app11041955

Stavropoulos, P., Papacharalampopoulos, A., Tzimanis, K., & Lianos, A. (2020). Manufacturing resilience during the coronavirus pandemic: On the investigation manufacturing processes agility. *European Journal of Social Impact and Circular Economy, 1*(3), 2–57.

Russell, S. J., Norvig, P., & Davis, E. (2010). *Artificial intelligence: A modern approach* (Prentice Hall series in artificial intelligence) (3rd ed.). Prentice Hall.

Tong, Q., Yang, M., & Zinetullina, A. (2020). A dynamic Bayesian network-based approach to resilience assessment of engineered systems. *Journal of Loss Prevention in the Process Industries, 65*, 104152. https://doi.org/10.1016/j.jlp.2020.104152

Wang, M. (2018). Impacts of supply chain uncertainty and risk on the logistics performance. *APJML, 30*, 689–704. https://doi.org/10.1108/APJML-04-2017-0065

Weichhart, G., Mangler, J., Raschendorfer, A., Mayr-Dorn, C., Huemer, C., Hämmerle, A., & Pichler, A. (2021). An adaptive system-of-systems approach for resilient manufacturing. *Elektrotechnik und Informationstechnik*. https://doi.org/10.1007/s00502-021-00912-2

Werner, M. J. E., Yamada, A. P. L., Domingos, E. G. N., Leite, L. R., & Pereira, C. R. (2021). Exploring organizational resilience through key performance indicators. *Journal of Industrial and Production Engineering, 38*, 51–65. https://doi.org/10.1080/21681015.2020.1839582

World Economic Forum. (2017). *The Global Risks Report 2017*. World Economic Forum. Accessed August 04, 2021, from http://www3.weforum.org/docs/GRR17_Report_web.pdf

Yang, S., Bian, C., Li, X., Tan, L., & Tang, D. (2018). Optimized fault diagnosis based on FMEA-style CBR and BN for embedded software system. *International Journal of Advanced Manufacturing Technology, 94*, 3441–3453. https://doi.org/10.1007/s00170-017-0110-y

Zhang, L., Pan, Y., Wu, X., & Skibniewski, M. J. (2021). Dynamic Bayesian networks. In L. Zhang, Y. Pan, X. Wu, & M. J. Skibniewski (Eds.), *Artificial intelligence in construction engineering and management* (pp. 125–146). Springer Singapore.

Chapter 9
Building Viable Digital Business Ecosystems with Collaborative Supply Chain Platform SupplyOn

Arvid Holzwarth, Cornelia Staib, and Dmitry Ivanov

Abstract Digital supply chains evolve toward business ecosystems that are becoming ever more complex and in which companies and supply chains collaborate in an increasingly networked manner. The viability consideration at the level of ecosystems can be supported by associated digital collaborative supply chain platforms. The COVID-19 pandemic times have clearly shown that the viability and ecosystem views are crucial when coping with and recovering from large-scale, massive crises. This chapter focuses on the current challenges of digital supply chains in the manufacturing industry and how they can be addressed. To this end, a concrete use case is highlighted at the Chinese premium car manufacturer Seres, where the Supplier Collaboration Portal SupplyOn with its integrated solutions has made a significant contribution to building ecosystem viability.

Keywords Digital supply chain · Resilience · Digital technology · End-to-end visibility · Data analytics · Business ecosystem · Viability · Digital collaborative supply chain platform

9.1 Introduction

Supply chain viability is an overarched resilience perspective that encapsulates ecosystem views and long-term survivability of business sectors (Ivanov, 2020). Supply chain resilience itself is the operational capability to withstand, adapt, and recover from disruptions to meet customer demand and ensure the target performance (Blackhurst et al., 2011; Hosseini et al., 2019; Pettit et al., 2019;

A. Holzwarth · C. Staib
SupplyOn AG, Hallbergmoos, Germany
e-mail: Info@SupplyOn.com

D. Ivanov (✉)
Department of Business and Economics, Supply Chain and Operations Management Group, Berlin School of Economics and Law, Berlin, Germany
e-mail: divanov@hwr-berlin.de

A. Dolgui et al. (eds.), *Supply Network Dynamics and Control*, Springer Series in Supply Chain Management 20, https://doi.org/10.1007/978-3-031-09179-7_9

Aldrighetti et al., 2021). From the viability perspective, it is essential for holistic resilience management to consider supply chain risks end-to-end and not just focus on individual risks (Ivanov, 2021a).

Across different stages of the COVID-19 pandemic, manufacturing and logistics have been coping with market, supply, and environmental uncertainties (Choi, 2020; Gupta et al., 2022; Ivanov & Das, 2020; Aldrighetti et al., 2021; El Baz & Ruel, 2021; Sodhi et al., 2021). Recent research posited the need for re-thinking of supply chain resilience from positions of viability, reconfigurable supply chains, socio-ecological and open system perspective learning from and thinking beyond the COVID-19 pandemic (Dolgui et al., 2020b; Hosseini et al., 2020; Ivanov, 2020; Ivanov & Dolgui, 2020; Azadegan & Dooley, 2021; Ruel et al., 2021). In particular, the key role of adaptability and digital technology has been debated in Rozhkov et al. (2022), Ivanov (2022), Ivanov et al. (2022), and Dolgui & Ivanov (2022).

The digital supply chains create new opportunities for resilience management and require a holistic re-thinking of organization, management, and technology (Kumar et al., 2018; Ivanov et al., 2019; Brintrup et al., 2020; Dolgui et al., 2020c; Dolgui & Ivanov, 2020; Dubey et al., 2021; Frazzon et al., 2021; Ivanov & Dolgui, 2021a; Sokolov et al., 2020; Zouari et al., 2021). If a supplier cannot meet up to his delivery obligations in scope, time, cost, and quality, and there is no qualified pre-agreed exception and mutually accepted justification of non-fulfilled delivery obligations, he will likely become subject to contract fines/penalties (Demirel et al., 2018; Aldrighetti et al., 2021; Gupta et al., 2021; Lücker et al., 2021). Furthermore, his reputation is damaged. In mid-term, he might not be considered trustworthy anymore and might be replaced by another, more reliable suppliers (Altay et al., 2018; Demirel et al., 2019; Ivanov, 2021a; Li et al., 2021). So, it is a question of long-term survival and viability to as early as possible identify and then mitigate future supply chain risk—in order to remain in business (Ivanov, 2020). Furthermore, the networking effects of disruptions can spread over the overall supply chain leading to the ripple effect (Dolgui et al., 2018, 2020a; Pavlov et al., 2020; Ghadge et al., 2021).

9.2 Data Completeness and Data Quality

9.2.1 Importance of Data Visibility to Cope with Supply Chain Disruptions and Crises

Visibility is one of the central resilience perspectives in supply chains (Christopher & Lee, 2004). In order to get from in-crisis risk fire-fighting to an early-warning system and supply chain tracking, allowing preventive actions, visibility of future demands plays a crucial role (Sheffi, 2015; Basole & Nowak, 2018; Ivanov et al., 2021; Ralston & Blackhurst, 2020; Nguyen et al., 2021). However, sometimes such data are not available as needed, or are outdated, or even just wrong. This leads to the question of how data completeness and data quality for forecast data can be addressed in a structured way (Waller & Fawcett, 2013; Papadopoulos et al., 2017; Das et al., 2019; Yang et al., 2019; Yoon et al., 2020; Winkelhaus & Grosse, 2020; Wamba & Queiroz, 2020).

The coronavirus crisis has revealed a long-standing challenge for suppliers even more clearly: How reliable are the demand forecasts they receive from their customers? High volatility and uncertainties in demand forecasting are not limited to pandemic times (Ivanov, 2021b, 2021c). Even in the "normal state," the originally reported requirements can differ considerably from the materials actually called off. The decisive question is therefore: How can forecasting be improved and thus also achieve a higher level of planning accuracy?

In an ideal world, a purchasing company sends a very stable demand signal to its suppliers for the next 12–18 months. The weekly or monthly updates of this forecast do not indicate any major, unexpected fluctuations. Moreover, the forecasts are also consistent with the quantities ordered and delivered in the end. This means that the supplier can always plan reliably—from material procurement through production to the actual work shifts, as delivery dates draw closer. The reality, however, usually looks quite different. Within the 12–18 months of a forecast period, adjustments and corrections to the demand forecasts are common. This is usually not a problem as long as the deviations are not too fundamental or too short-term. A few weeks ahead of the actual production, in the so-called firm horizon, things should not change too much anymore.

Procurement of raw materials usually requires long lead time. Thus, short-term changes such as "please deliver two weeks earlier, but in lesser quantities" or "we need the materials one week later, but in double the quantity" present the supplier with major, sometimes insurmountable challenges. Quite often, the fluctuation margins depicted in the forecast are not adhered to in practice. As a consequence, high demand volatility can lead to delivery disruptions, especially reported just before the call-off (Adelhardt, 2020).

To complicate matters during the pandemic, suppliers were sometimes faced with a system-imminent inertia (Ivanov & Rozhkov, 2020). In some cases, ERP processes ran completely automatically, i.e., not dynamically adapted to the new situation. Forecasts may have still been based on a sales plan that was created several months or quarters ago. Particularly in the event of rapid economic upheavals, suppliers can then no longer rely on the submitted demands (Cavalcante et al., 2019; Currie et al., 2020; Queiroz et al., 2020). Although the forecasts are later usually corrected, this often happens very shortly before the call-off or even just before the actual delivery date. It is not just that the updated demands then differ considerably from the forecast just 1 week earlier. Also, these corrections often bypass the ERP system. In many cases, email, phone and fax serve as the emergency line.

However, suppliers plan their material procurement and other internal production steps well in advance—based on the reported ERP figures. Of course, contracts include provisions regarding the quantities of purchases in the short-term horizon. However, upward adjustments of quantities during this period may pose serious challenges for the security of supply. These, therefore, need to be recognized or avoided (Adelhardt, 2020).

9.2.2 Partnership and Trust

In the end, a well-organized supply chain is not only built upon defined contracts and working processes and tools but also by people from different business partners who know each other, know, accept and live the collaboration rules, processes and use the available toolset (MacCarthy & Ivanov, 2022; Ivanov et al., 2022; Dolgui & Ivanov, 2022). Essential for such a collaboration is an established partnership, where each piece of the supply chain does not only take responsibility for its own internal processes, but also for the interfaces and communication flow with the supply chain partners—for a living and working business partnership (Giannoccaro & Iftikhar, 2021). The basis for such a partnership is trust in the capabilities, reaction time, and service orientation of the business partner with his team—in the end, it is not only about organizations working together, but also about people.

9.3 Digital Supply Chain: Vision and Technology

9.3.1 Vision of a Digital Supply Chain

Digital supply chains aim at making better use of the information from the different internal and external IT systems. The vision for a viable digital supply chain should incorporate the following aspects (Ivanov et al., 2019; Panetto et al., 2019; Tang & Veekenturf, 2019; Queiroz et al., 2019; Dubey et al., 2021; Ivanov & Dolgui, 2020; Ruel et al., 2021; Zouari et al., 2021):

- End-to-end visibility, with an early-warning system
- Achieving a more reliable planning despite demand fluctuations
- Insights where deviations from expected supply chain performance come from
- Identification and tracking of appropriate risk mitigation actions (Reng, 2020)
- Smooth supply chains despite high demand volatility

In brief, if such a vision comes true, affected business partners would benefit from:

- Reliable and early identification of demand patterns and fluctuation bandwidths
- Improving planning reliability by enriching forecasts with historical data and trend analyses at customer, plant, and material level
- Avoiding short-term rescheduling and adjustments in production
- Preventing laborious or expensive ad-hoc material orders
- Eliminating supply disruptions to the customer

- Optimizing stock management
- Increasing customer satisfaction and loyalty, since the supplier is able to quickly respond to changes in demand, even at short notice
- Understanding the cause of fluctuations in-depth (why, when, and where these usually occur). This allows for designing targeted prevention and mitigation measures jointly with their customers.

Ultimately, this would benefit all supply chain participants, from the purchasing company all the way to the sub-supplier. After all, there will be fewer disruptions and, as a result, the supply chain will be generally more resilient.

Companies would no longer pass on uncertainties about the current order and demand situation further down the supply chain. Instead, they can achieve some state of predictability and robustness even in uncertain times. This in turn would benefit the supply chain as a whole. The so-called new normal of a VUCA world (VUCA = volatility, uncertainty, complexity, ambiguity) thus could become more manageable (Adelhardt, 2020).

9.3.2 Digital Supply Chain Technology

SaaS

As a strong trend, the technology software-as-a-service becomes more and more common, as it does not require local installations and can be accessed from everywhere and independent from specific hardware, as long as it meets the defined technology requirements. In this context, the right balance has to be found between public and private clouds, as a public approach is helpful for managing a diversified holistic supply chain, while a private cloud secures data confidentiality.

Using the same platform

To avoid non-value add media breaks and leverage synergies across the supply chain, connecting all tier levels via one global business network makes sense. Furthermore, economies of scale can be leveraged, if, e.g., the same supplier user uses the same platform via single sign-on, to collaborate with different customers.

Using the same processes

Synergies are fostered, if cross-functional departments (internal & external) use the same multi-enterprise supply chain collaboration platform. Ideally, all relevant business processes are supported in an industry solution portfolio. Likewise, if several tier levels use the same processes, and such processes are improved, this then benefits the whole vertical supply chain.

Using the same data formats

If an industry solution portfolio is used, the same data format facilitates data exchange (e.g., if the same PO format is used not only for all inbound suppliers but also toward own customers). Furthermore, industry-specific have to be respected, e.g., EDIFACT for Automotive and manufacturing processes, SPEC2000 for MRO processes, or BoostXML for Aerospace processes.

Using the same high-security standards
At the heart of data security are confidentiality and integrity of business partner data as well as availability of services (Dolgui et al., 2020c; Lohmer et al., 2020). Such security standards have to be met. Confidentiality in this context means that data, objects, and resources are protected from unauthorized access. Integrity means that data is protected from unauthorized changes to ensure that it is reliable, not manipulated and correct. Availability means that authorized users always have access to the systems and the resources they need. No doubt, security standards along the whole supply chain have to be met, as any weak point at just one point of the supply chain cannot be compensated by the other chain elements.

9.4 How SupplyOn Helps to Foster Resilience and Viability

9.4.1 Managing the Supply Chain Complexity in the Context of Digital Transformation

SupplyOn is a vertical Software-as-a-Service supply chain business network, which was founded in 2000 and connects business partners like customers, their suppliers and carriers. As public-private cloud, SupplyOn on the one side is public: It is a B2B portal available via the web, via www.supplyon.com, for registered users with dedicated user privileges based on SupplyOn's user rights and roles concept. On the other hand, the data are private: this user rights and roles concept secures that each user of a business partner only has access to the data which she or he is entitled to see. Connected business partners benefit from a defined configurable subset of the available business suite processes in SupplyOn, as explained further below.

As an early-warning system for the B2B supply chain, SupplyOn fosters collaboration and transparency between the business partners, supports compliance, quality, and security of supply and reduces non-value-add work, e.g., by avoiding media breaks.

SupplyOn connects business partners worldwide and ensures the long-term success of supply chains. SupplyOn's business partners benefit from this dynamic company network that connects more than 100,000 businesses in over 100 countries worldwide. This network can be used to quickly adapt to market changes and supply chain dynamics. While digital transformation has long been state-of-the-art in production, it is still a challenge when working with suppliers. Business partners are too numerous and too different, their systems, structures, and mindset vary too widely. SupplyOn makes this complexity manageable.

An experienced consulting team supports companies to adapt and integrate the new processes in just a short time and to get all parties involved in the new processes ready for digital collaboration. SupplyOn offers a broad and integrated supply chain solution portfolio for the specific process requirements of the automotive, aerospace, railway, and manufacturing industries. This solution portfolio reproduces all of the processes in the digital supply chain in a structured, transparent and secure manner—whether the goods to be procured are production materials, services or indirect material; regardless of how big a business partner is and where they are located. It supports processes for supplier management, purchasing, procurement, logistics, transport, quality, and risk management. With innovative solutions for visualization, analysis, and artificial intelligence, the entire supply chain can be controlled safely, efficiently, and intelligently in a dynamic global environment.

SupplyOn is committed to the manufacturing industry. The solution portfolio covers industry-specific features in the automotive, aerospace, railway, and engineering industries. Due to the high degree of overlapping, individual industry communities are then merged into a vast worldwide corporate network for the manufacturing industry.

Being part of the SupplyOn supply chain business network, allows to leverage synergies from a strong industry community, benefitting from agreed standards, mutual exchange, already existing solutions and also from cost sharing, if the existing industry standard is being extended. In such a scenario, business partners never walk alone.

SupplyOn was founded in 2000—shortly after the bursting of the dot-com market. Thanks to a forward-looking and sustainable business model SupplyOn is thriving today and represented in important and potentially fastest-growing markets around the world. In addition to its headquarters near Munich, SupplyOn has locations in China (Shanghai) and various locations in the USA.

SupplyOn has not only driven its growth organically but also made two strategic acquisitions: In January 2017 the company acquired Newtron, a provider of holistic procurement solutions, which focuses in particular on non-production material and catalog products. These solutions complemented SupplyOn's solution portfolio, which focused more on production material. In February 2018 SupplyOn acquired Euro-Log AG, a provider of transport management solutions, thus creating value add for a fully integrated supply chain and transport management solution in discrete manufacturing. Among its customers are such industrial enterprises as Airbus Group, BMW Group, Bombardier, BorgWarner, Bosch, Continental, Deutsche Bahn, DEUTZ, Kautex Textron, Liebherr, Oerlikon, Safran, Schaeffler, Schindler, Siemens, Thales, and ZF. SupplyOn shareholders are Robert Bosch GmbH, Continental AG, ZF Friedrichshafen AG and Schaeffler AG.

9.4.2 *SupplyOn Security Approach*

Confidentiality, availability, and integrity of customer information are of the highest priority for SupplyOn.

Process and Security Management

SupplyOn aims to establish necessary security to protect Confidentiality and Integrity of Customer Data as well as high availability of SupplyOn Services.

SupplyOn, therefore, has established the necessary processes and a certified Information Security Management System (ISMS):

- Certified Security-Management, ideally according to ISO 27001, ISO 27017, and ISO 27018, as information security management, using defined controls, also for cloud service providers and for data security topics,
  see https://www.supplyon.com/security
- External assessments based on Industry Security Standards (e.g., TISAX based on ISO 27001 with additional questions: Trusted Information Security Assessment Exchange, used by European automotive companies)
- Secure software development process
- Regular audits and penetrations tests
- ITIL-based service management (framework for IT service management)

Data Privacy

Data privacy should follow:

- Data privacy management according to European Privacy Laws and Regulations (EU-GDPR), involving also an external data security officer for legal questions
- Fine-Grained Rolls- and Rights Concept: only persons with direct business relations see each other's contact data
- Separate Environments for production, quality assurance and development:
  development environments only see test data/anonymized data
- Delegated User-Administration: a company supplier administrator can administrate, e.g., his/her colleagues.

Data and Application Strategy

Data and application strategy benefit from:

- Policy for strong user passwords (intelligent libraries how secure the password is)
- Controlled administration access

- Vulnerability and patch management (automated monthly security scans)
- Encryption of Data-in-Transit using TLS (Transport Layer Security)
- Single-Sign-On and Federation-Integration (e.g. customer employee portal)
- Data-at-Rest Encryption for Classified Data plus data-in-transit encryption
- Optional certificate-based User Authentication (customers where their users have already digital certificates can be used for two-factor-authentification).

Security Infrastructure

Secure infrastructure with our hosting partner TDS is based on:

- Modern data centers (ISO and BSI-certified; two different sites)
- Automated Security-Checks
- Central backup infrastructure
  (architecture design for high availability with mirroring)
- Network- and Server-Monitoring (24/7)
- Intrusion detection and prevention
- Virus-Protection and Multi-Layer Firewall
  Architecture designed for High-Availability

9.5 Building a Digital Supply Chain Platform: How SupplyOn Supports the Supply Chain in the Automotive Industry

End-to-end demand and delivery processes as well as the application of innovative logistics concepts are key for successful organizations (Choi et al., 2018; Cai et al., 2021). Smooth and transparent processes between manufacturing companies and their suppliers are particularly critical in operational procurement in order to maintain the flow of materials and thus keep the production up and running. To that end, solutions from SupplyOn provide more than the pure data transmission between the companies involved in this cooperation. They provide a shared view of the actual supply situation thus allowing to efficiently control the whole supply chain.

Classic demand processes, such as delivery instructions and call-offs, are supplemented by consumption-controlled logistics concepts such as Vendor Managed Inventory and Kanban. This provides companies with all the essential processes to successfully manage the entire collaboration with their global supplier base.

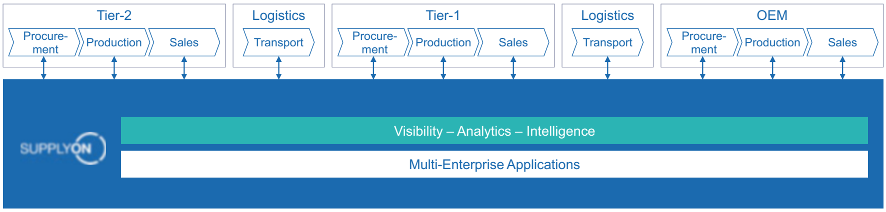


Fig. 9.1 Supply chain visibility (SupplyOn, 2022)

SupplyOn's value proposition is as follows (Fig. 9.1):

1. Connecting and enabling of all tier levels via one global business network
2. Cross-functional departments (internal and external) use the same multi-enterprise supply chain collaboration platform
3. All relevant business processes are supported in an industry solution portfolio
4. Visibility, analytics, and intelligence create supply chain visibility and enable Intelligent Automations (Kastl, 2020)
5. Data Sovereignty stays with the data owner.

SupplyOn's vision of the supply chain is autonomous, highly adaptive supply chains working with autonomous enterprises (Fig. 9.2).

9.5.1 Overview of the SupplyOn Solution Suite

The SupplyOn solution suite supports collaboration between business partners throughout the whole product lifecycle. Figure 9.3 illustrates the SupplyOn digital platform.

9.5.2 Deep Dive for Demand Processes

With SupplyOn, business partners have all classic requirement processes available to automatically transmit data from their internal systems to their suppliers:

- Delivery instructions, which are used to inform such suppliers of the planned net requirements based on a general agreement
- Call-offs, which are used to order a certain quantity for a specific time based on delivery instructions
- Purchase orders, which are used to efficiently handle all requirements that cannot be easily standardized
- Requirement reminders that remind suppliers of overdue or upcoming deliveries

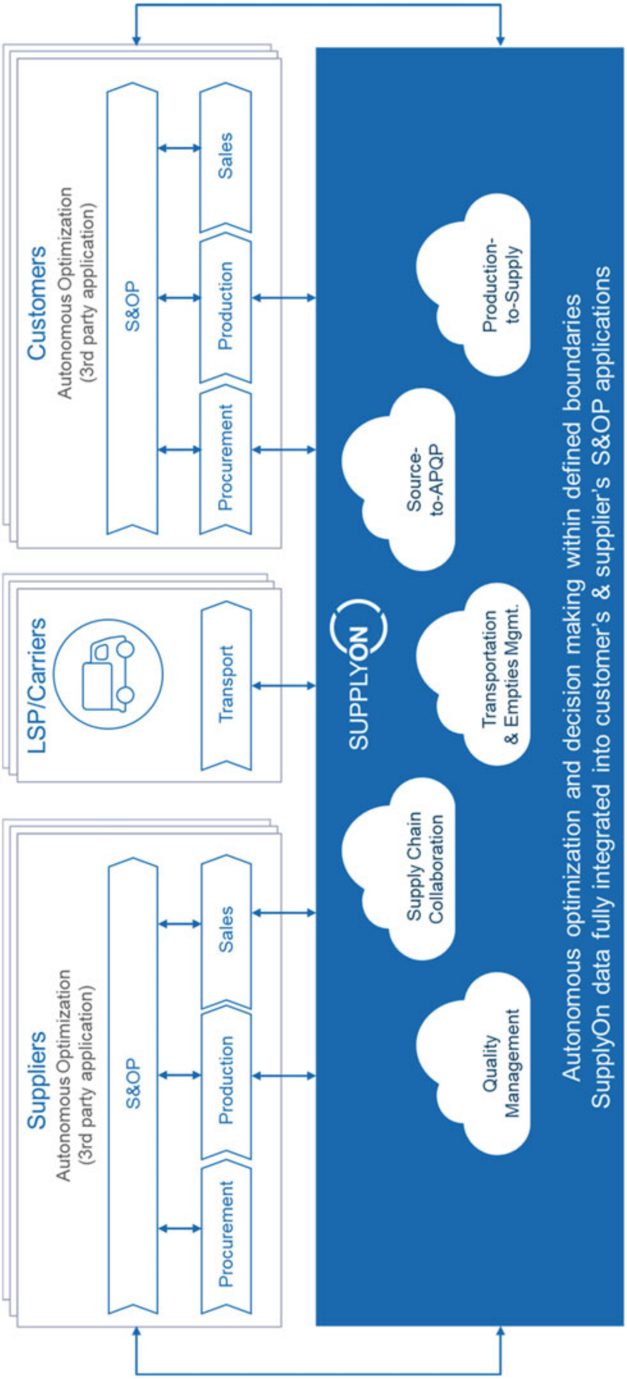


Fig. 9.2 Digital supply chain (SupplyOn, 2022)

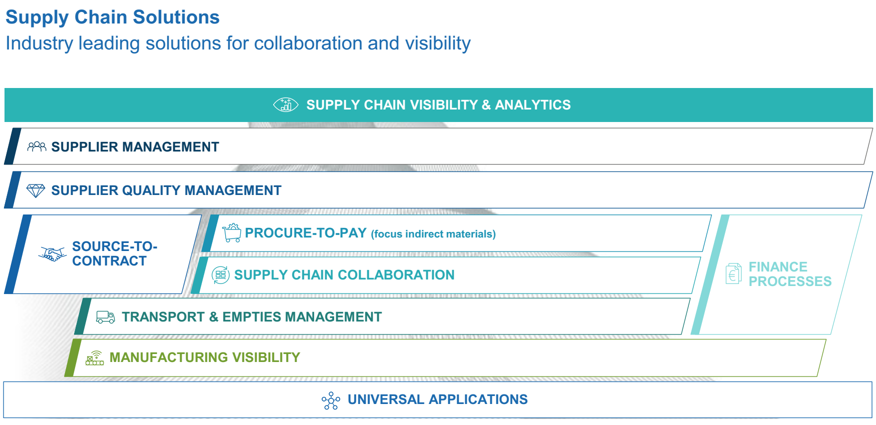


Fig. 9.3 SupplyOn digital platform (SupplyOn, 2022)

But to have a functioning logistics management system, business partners need more than just the ability to send and display these messages. SupplyOn also provides them with an early warning system for the order and delivery process which ensures processes run smoothly. With individually adjustable reminder functions, business partners can identify disruptions in the supply chain at an early stage and respond promptly. For example, the system automatically sends a reminder to all parties for pending order confirmations or overdue deliveries.

9.5.3 Deep Dive for Advance Shipping Notification

The Advance Shipping Notification informs customers promptly of delivery and transportation details, when they can expect where arrival of which quantities of materials, with related information. In particular in the case of complex supply chains, it is vital for a SupplyOn customer's requirements planning department to be informed of upcoming goods consignments promptly and extensively. That is because unscheduled goods receipts or deliveries which cannot be handled or can only be processed with considerable effort due to false labels, barcodes, or packaging cost valuable time and money.

With the electronic Advance Shipping Notification (ASN) in SupplyOn, buying companies know exactly what their supplier will deliver where, when, and in what quantity. The advantage of the electronic process is obvious: When their supplier creates an Advanced Shipping Notification, it already contains information from the original order or the delivery instruction. That means this supplier only has to add a few more details relating to the packaging, volume, and transportation. Well before the goods are received, related dispatchers, therefore, receive all the information they need to make the necessary preparations for receiving the goods.

9.5.4 Deep Dive for Goods Receipt

SupplyOn enables fast and easy reception of delivered parts, thus optimizing related processes during goods receipt. Buyside employees in the goods receipt department are promptly informed about upcoming goods consignments via the upstream advance shipping notification process. Labels and barcodes generated by SupplyOn ensure that the goods are correctly booked into the system. Simple scanning of the labels is sufficient. Such a supplier just needs to print out the correct labels in the system.

Via the optional paperless goods receipt process, certain document types accompanying the delivery, e.g., needed quality documents, like certificates of conformity, can be made mandatory already for the Advance Shipping Notification. The acceleration of business partner's processes during goods receipt saves valuable time and thus money.

9.5.5 Deep Dive for Finance Processes

Paper invoices are still common with some suppliers. But paper-based invoice processes are not only inefficient as the information needs to be keyed in again in the customer system. Moreover, they are also prone to errors, due to typos or missing information. Many companies have therefore started to digitize their suppliers' invoices, via scan shops or optical character recognition (OCR). However, this does not resolve the issue of low automatic booking rates as sometimes, mandatory information on the invoice is missing, illegible, or interpreted in a deviating way. On other invoices, information like the purchase order (PO) reference may be incorrect. All of this results in time-consuming and expensive correction loops. Typical challenges for invoices will be different for the customer and his suppliers.

For the customer, it is typically about procurement cost, process cost, IT landscape topics and company issues. Typical examples are high manual efforts to check incoming invoices, error-prone media breaks, incomplete invoice data and intransparent invoice status, causing inefficiences, expensive errors and additional workload. Mostly, customers try to correct the errors as quickly and specifically as possible by using workflow machines. SupplyOn does not want it to come to that. SupplyOn wants to increase the quality of the invoice information so that no corrective measures are necessary. The invoices should be posted quickly and automatically at the customer's premises.

For the supplier, of course, invoice creation is always at the heart of his own interest, as he wants to get paid. However, manual invoice creation is error-prone, time-consuming, and often accompanied by a lack of transparency if, e.g., inquiries are needed and no standards are available (e.g., if an inquiry takes place in an unstructured e-mail, not technically linked to the underlying invoice). Inquiries from suppliers often refer to the status of invoices or lost track of queries and disputes.

SupplyOn Purchase-to-Pay is an integrated end-to-end process flow, from electronic order creation, confirmation, delivery, invoice creation, invoice check, automatic booking of the invoice in the customer ERP, to payment—and with the SupplyOn Finance Portal even comprises requests/dunning linked to the invoice (Fig. 9.4).

Automatic Data Transfer from PO, DA/ASN and Master Data Pool to an invoice form secures a high invoice data quality. This completeness and quality of information ensure a high auto-booking rate, so manual checks of invoices will become a rare exception. Depending on the parent processes for invoices integrated in the complete process, different automation rates can be achieved. Best results are achieved by E2E visibility, based on predecessor-based processes. Depending on the supplier's needs, invoice volume, and technical maturity, SupplyOn can offer different channels for the suppliers, to submit their invoices—from the PO flip function which allows invoice creation directly in the portal, via machine-readable CSV or PDF upload, or full EDI integration, e.g., via EDIFACT or UBL XML.

With SupplyOn digital predecessor-based processes, e-invoicing is improved. Here, the electronic invoice is based on an electronic PO or advance shipping notification (ASN). Thus, the integrated SupplyOn Purchase-to-Pay (P2P) solution suite enables transparent and efficient collaboration, from demand generation to delivery, goods receipt, invoice creation, invoice booking and payment.

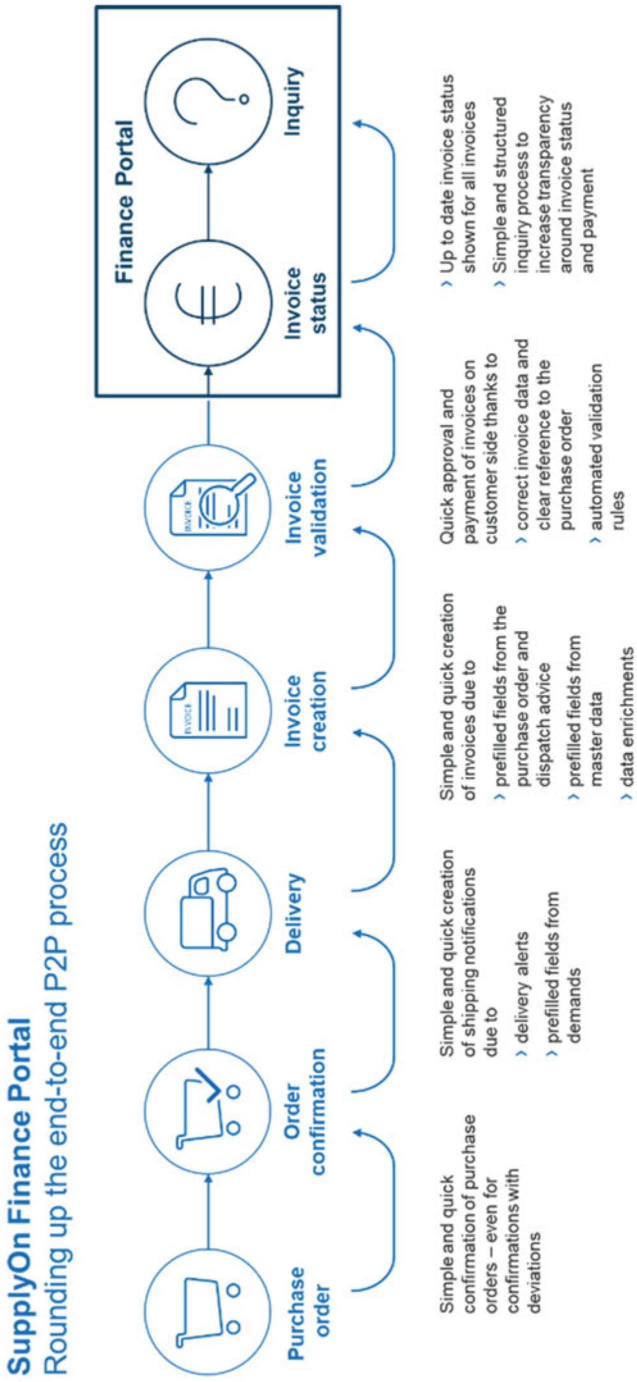


Fig. 9.4 SupplyOn finance portal (SupplyOn, 2022)

9.6 Case Study Seres

9.6.1 The Art of Manufacturing Electronic Vehicles at Seres Automobile

Source: Seres Automobile, 2019

Seres Automobile, the subsidiary of the Chinese Sokon Industry Group dedicated to new energy vehicles, partners with SupplyOn to build and manage its global supply chain. “The production of electric vehicles must be based on smart manufacturing. This is a holistic, new business model which takes user needs into account. Therefore, it must also innovate, change and improve the entire supply chain system,” said Huang Lei, Vice President of the Chongqing Sokon Industry Group. As Vice President of the Chongqing Sokon Industry Group, Huang Lei is pursuing a clear goal: to build a complete supply chain system from scratch for the intelligent production of the new electric vehicle.

Huang Lei is convinced that the new drive technology combined with new production methods also requires a new business model. Seres Automobile, the subsidiary of the Chinese manufacturing giant Sokon that was founded specifically for this purpose, therefore uses the so-called customer-to-manufacturer (C2M) approach.

9.6.2 The Challenge of C2M

Huang Lei, Vice President at Sokon, is the mastermind of Seres' supply chain strategy. The basic idea behind the C2M model is its high user focus, which enables tailor-made adaptations. Production is organized according to the individual needs of the customer. This allows consumers to actively participate in product design. This in turn places higher demands on the supply chain.

"C2M requires appropriate capacity building, supply chain modernization and optimization of both organizational structures and business relationships," explains Huang Lei. From the outset, Seres focused on the enhancements of supply chain capabilities to gain a competitive advantage in the electric vehicle market. The manager is convinced that the supply chain is the backbone for products and marketing.

9.6.3 Seres' "321 Supply Chain System"

This is why Seres set up a so-called 321 Supply Chain System for smart manufacturing. According to Huang Lei, this system consists of three components:

- Three circles: These three circles consist of data collection, analysis and interpretation and feedback for improvement. Together they form a closed loop. The data for this comes from the SupplyOn platform.
- Two chains: For intelligent manufacturing, the supply chain (i.e., purchase order) and the production chain (i.e., sales' order or customers' voices in terms of demand) are closely coordinated and interlinked.
- One pyramid: Seres is organized in the form of a nine-level pyramid—from the production site to the sensor technology to control and finally to sales.

9.6.4 From Traditional Supply Chain to Supply Chain Ecosystem

Everything is new in electric vehicles: the organization, the models, the management, the suppliers. Equally new is the way of thinking about and approaching the supply chain as a whole. An essential role plays the concept of ecosystems, here. Thus, Seres places great emphasis on collaborating closely with its suppliers, from access to other suppliers and product development to the coordination of supply and demand.

The example of the COVID-19 pandemic shows that in case of extraordinary events, supply chain resistance to disruptions needs to be considered at the scale of survivability or viability to avoid supply chain and market collapses and secure the provision with goods and services (Ruel et al., 2021). According to Ivanov and

Dolgui (2020), "*viability is a behavior-driven property of a system with structural dynamics. It considers system evolution through disruption-reaction balancing in the open system context. The viability analysis is survival-oriented at a long-term scale.*" Ivanov (2020) defines viability as an "*ability of a supply chain to maintain itself and survive in a changing environment through a redesign of structures and replanning of performance with long-term impacts."*

The viable supply chain model and the associated frameworks have been proposed by Ivanov (2020) and is comprised of the supply chain itself, the intertwined supply network (ISN) which is an "*entirety of interconnected supply chains which, in their integrity secure the provision of society and markets with goods and services*" (Ivanov & Dolgui, 2020), a digital supply chain which represents in a combination with the physical SC a cyber-physical system and a digital supply chain twin (Cavalcante et al., 2019; Panetto et al., 2019; Ivanov & Dolgui, 2021b; Frazzon et al., 2021), and a business ecosystem responsible for securing society needs in line with nature, economy and governance interests.

A key reason why Seres Automobile chose SupplyOn was its large ecosystem, which includes more than 100,000 companies and suppliers in the production sector worldwide. Moreover, having R&D facilities in the USA and a clear growth target, the SupplyOn network will help Seres to achieve smooth collaboration on a global scale. In addition, the numerous best-practice examples for rapid supplier onboarding also helped to convince the Chinese electric vehicle manufacturer.

9.6.5 Seres Smart Manufacturing Is Based on Three Pillars

A prerequisite for intelligent production is the appropriate technological support. Liu Yusheng, head of the Sokon Seres Automotive Intelligent Manufacturing project, focuses on three areas: "We use '3T' for intelligent manufacturing: Operation Technology (OT), Information Technology (IT) and Automation Technology (AT)."

Right from the initial development of its IT platform, Seres also designed the supply chain management (SCM) system alongside other core systems such as MOM (Manufacturing Operations Management) and ERP. Liu Yusheng is convinced that supply chain collaboration plays a decisive role in the manufacturing value chain. For Seres, it was particularly important that this supplier collaboration be completely digitized from the very beginning.

9.6.6 A Flexible SCM Platform for Global Needs

The SupplyOn platform supports all of Seres' business processes with its suppliers: From Supplier Management through Source-to-Contract (strategic sourcing and contract synchronization) and classic Supply Chain Collaboration (Forecast, PO, JIS/JIT, ASN, Goods Receipt, etc.) to Procure-to-Pay and eInvoicing. This full-cycle collaboration across the entire production process ensures high efficiency and transparency. It creates a comprehensive data pool, which opens up a wide range of analysis options, for example for optimizing the supply chain or supplier performance.

From the very beginning, Seres pursued a global, cross-functional and holistic strategy with its SCM project. Across the companies, everyone was to be able to use the same basis and benefit from synergy effects. At the same time, the different needs in the individual regions had to be considered. All this is made possible by the standardized SupplyOn platform, which meets the different regional requirements through flexible process configurations.

In China, for example, the platform supports both eInvoicing and the Golden Tax invoicing process via Fapiao. In the USA, by contrast, the integrated Procure-to-Pay (P2P) process has been set up. Similar regional differences are also implemented in sourcing, for example. Implementation took place in two phases, grouped according to strategic and operational processes. Although Seres as a company started out right from scratch, the first phase was finished within just 6 months. Another 6 months later, further enhancements and refinements were implemented—and the first 200 suppliers connected.

In summary, to best meet the challenges of the Chinese electric vehicle market, Seres New Energy Automobile has established a completely new supply chain management system. As a technology partner, the Chinese electric vehicle manufacturer relied on SupplyOn as the global management system for all collaboration processes with suppliers. This forms the foundation for the success of the Customer-to-Manufacturing (C2M) approach in the context of smart manufacturing.

9.7 Conclusion

Supply chains are exposed to both positive and negative disruptions (MacCarthy et al., 2016; Dolgui & Ivanov, 2020). As a positive disruption, digital technology adoption in companies contributes to the development of digital supply chains (Ardolino et al. 2022; Dubey et al. 2019; Roeck et al. 2020; Xiao 2020; SupplyOn 2022). As negative disruptions, fires, tsunamis, strikes, and pandemics challenge supply chain resilience that has become a central perspective in a world that is becoming ever more complex and in which companies and supply chains are working together in an increasingly networked manner.

This chapter focuses on the current challenges of digital supply chains in the manufacturing industry and how they can be addressed. To this end, a concrete use case was highlighted at the Chinese premium car manufacturer Seres, where the Supplier Collaboration Portal SupplyOn with its integrated solutions has made a significant contribution to significantly increasing supply chain resilience and ecosystem viability.

We conclude that while resilience of individual firms is important and crucial in many settings, the digital supply chain evolves toward business ecosystems. The resilience consideration at the level of ecosystems and associated digital collaborative supply chain platforms is related to viability. The COVID-19 pandemic times have clearly shown that the viability and ecosystem views are crucial when coping with and recovery from large-scale, massive crises. Fluctuations in demand on the customer side pose enormous challenges for companies and their suppliers. In times of crisis, such as a pandemic or recession, it becomes even more difficult, not only during the crisis itself, but especially for the re-ramp-up after the crisis has passed. As such the role of digital supply chain platforms such as SupplyOn in designing more resilient supply chains and viable business ecosystems will be increasing in future and we expect new and impactful research in this area coming with technological developments.

References

Aldrighetti, R., Battini, D., Ivanov, D., & Zennaro, I. (2021). Costs of resilience and disruptions in supply chain network design models: A review and future research directions. *International Journal of Production Economics, 108103*. https://doi.org/10.1016/j.ijpe.2021.108103

Altay, N., Gunasekaran, A., Dubey, R., & Childe, S. J. (2018). Agility and resilience as antecedents of supply chain performance under moderating effects of organizational culture within humanitarian setting: A dynamic capability view. *Production Planning and Control, 29*(14), 1158–1174.

Ardolino, M., Bacchetti, A., & Ivanov, D. (2022). Analysis of the COVID-19 pandemic's impacts on manufacturing: A systematic literature review and future research agenda. *Operations Management Research*. https://doi.org/10.1007/s12063-021-00225-9

Azadegan, A., & Dooley, K. (2021). A typology of supply network resilience strategies: Complex collaborations in a complex world. *Journal of Supply Chain Management, 57*(1), 17–26.

Basole, R. C., & Nowak, M. (2018). Assimilation of tracking technology in the supply chain. *Transportation Research Part E: Logistics and Transportation Review, 114*, 350–370.

Blackhurst, J., Dunn, J., & Craighead, C. (2011). An empirically derived framework of global supply resiliency. *Journal of Business Logistics, 32*(4), 347–391.

Brintrup, A., Pak, J., Ratiney, D., Pearce, T., Wichmann, P., Woodall, P., & McFarlane, D. (2020). Supply chain data analytics for predicting supplier disruptions: A case study in complex asset manufacturing. *International Journal of Production Research, 58*(11), 3330–3341.

Cai, Y., Choi, T. M., & Zhang, J. (2021). Platform supported supply chain operations in the blockchain era: Supply contracting and moral hazards. *Decision Sciences, 52*(4), 866–892.

Cavalcante, I. M., Frazzon, E. M., Forcellinia, F. A., & Ivanov, D. (2019). A supervised machine learning approach to data-driven simulation of resilient supplier selection in digital manufacturing. *International Journal of Information Management, 49*, 86–97.

Choi, T. M., Wallace, S. W., & Wang, Y. (2018). Big data analytics in operations management. *Production and Operations Management, 27*(10), 1868–1883.

Choi, T.-M. (2020). Risk analysis in logistics systems: A research agenda during and after the COVID-19 pandemic. *Transportation Research Part E: Logistics and Transportation, 140*, 101961.

Christopher, M., & Lee, H. (2004). Mitigating supply chain risk through improved confidence. *International Journal of Physical Distribution & Logistics Management, 34*(5), 388–396.

Currie, C. S. M., Fowler, J. W., Kotiadis, K., Monks, T., Onggo, B. S., Robertson, D. A., & Tako, A. A. (2020). How simulation modelling can help reduce the impact of COVID-19. *Journal of Simulation, 14*(2), 83–97.

Das, A., Gottlieb, S., & Ivanov, D. (2019). Managing disruptions and the ripple effect in digital supply chains: Empirical case studies. In D. Ivanov et al. (Eds.), *Handbook of Ripple Effects in the Supply Chain* (pp. 261–285). Springer.

Demirel, G., MacCarthy, B. L., Ritterskamp, D., Champneys, A., & Gross, T. (2019). Identifying dynamical instabilities in supply networks using generalized modeling. *Journal of Operations Management, 65*(2), 133–159.

Demirel, S., Kapuscinski, R., & Yu, M. (2018). Strategic behavior of suppliers in the face of production disruptions. *Management Science, 64*(2), 533–551.

Dolgui, A., Ivanov, D., Potryasaev, S., Sokolov, B., Ivanova, M., & Werner, F. (2020c). Blockchain-oriented dynamic modelling of smart contract design and execution control in the supply chain. *International Journal of Production Research, 58*(7), 2184–2199.

Dolgui, A., & Ivanov, D. (2020). Exploring supply chain structural dynamics: New disruptive technologies and disruption risks. *International Journal of Production Economics, 229*, 107886.

Dolgui, A., Ivanov, D., & Rozhkov, M. (2020a). Does the ripple effect influence the bullwhip effect? An integrated analysis of structural and operational dynamics in the supply chain. *International Journal of Production Research, 58*(5), 1285–1301.

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.

Dolgui, A., Ivanov, D., & Sokolov, B. (2020b). Reconfigurable supply chain: The X-Network. *International Journal of Production Research, 58*(13), 4138–4163.

Dolgui, A., & Ivanov, D. (2022). 5G in digital supply chain and operations management: Fostering flexibility, end-to-end connectivity and real-time visibility through internet-of-everything. *International Journal of Production Research, 60*(2), 442–451.

Dubey, R., Gunasekaran, A., Childe, S. J., Wamba, S. F., Roubaud, D., & Foropon, C. (2021). Empirical investigation of data analytics capability and organizational flexibility as complements to supply chain resilience. *International Journal of Production Research, 59*(1), 110–128.

Dubey, R., Gunasekaran, A., Childe, S. J., Blome, C., & Papadopoulos, T. (2019). Big data and predictive analytics and manufacturing performance: Integrating institutional theory, resource-based view and big data culture. *British Journal of Management, 30*(2), 341–361.

El Baz, J., & Ruel, S. (2021). Can supply chain risk management practices mitigate the disruption impacts on supply chains' resilience and robustness? Evidence from an empirical survey in a COVID-19 outbreak era. *International Journal of Production Economics, 233*, 107972.

Frazzon, E. M., Freitag, M., & Ivanov, D. (2021). Intelligent methods and systems for decision-making support: Toward digital supply chain twins. *International Journal of Information Management, 57*, 102281.

Ghadge, A., Er Kara, M., Ivanov, D., & Chaudhuri, A. (2021). Visualisation of ripple effect in supply chains under long-term, simultaneous disruptions: A System Dynamics approach. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2021.1987547

Giannoccaro, I., & Iftikhar, A. (2021). Mitigating ripple effect in supply networks: The effect of trust and topology on resilience. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2020.1853844

Gupta, S., Starr, M. K., Zanjirani Farahani, R., & Asgari, N. (2022). Pandemics/epidemics: Challenges and opportunities for operations management research. *Manufacturing and Service Operations Management, 24*(1), 1–23.

Gupta, V., Ivanov, D., & Choi, T.-M. (2021). Competitive pricing of substitute products under supply disruption. *Omega, 101*, 102279.

Hosseini, S., Ivanov, D., & Blackhurst, J. (2020). Conceptualization and measurement of supply chain resilience in an open-system context. *IEEE Transactions on Engineering Management*. https://doi.org/10.1109/TEM.2020.3026465

Hosseini, S., Ivanov, D., & Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transportation Research Part E: Logistics and Transportation Review, 125*, 285–307.

Ivanov, D. (2022). Blackout and supply chains: Performance, resilience and viability impact analysis. *Annals of Operations Research*. https://doi.org/10.1007/s10479-022-04754-9

Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "supply chain-as-a-service". *Transportation Research – Part E: Logistics and Transportation Review, 160*, 102676.

Ivanov, D. (2020). Viable Supply Chain Model: Integrating agility, resilience and sustainability perspectives – lessons from and thinking beyond the COVID-19 pandemic. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03640-6

Ivanov D. & Das A. (2020). Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: A research note. *International Journal of Integrated Supply Management, 13*(1), 90–102.

Ivanov, D. (2021a). *Introduction to supply chain resilience*. Springer Nature, ISBN 978-3-030-70490-2.

Ivanov, D. (2021b). Exiting the COVID-19 pandemic: After-shock risks and avoidance of disruption tails in supply chains. *Annals of Operations Research*. forthcoming.

Ivanov, D. (2021c). Supply chain viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. *International Journal of Production Research, 59*(12), 3535–3552

Ivanov, D., Tang, C. S., Dolgui, A., Battini, D., & Das, A. (2021). Researchers' perspectives on Industry 4.0: Multi-disciplinary analysis and opportunities for operations management. *International Journal of Production Research, 59*(7), 2055–2078.

Ivanov, D., & Dolgui, A. (2021a). A digital supply chain twin for managing the disruptions risks and resilience in the era of Industry 4.0. *Production Planning and Control, 32*(9), 775–788.

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability: A position paper motivated by COVID-19 outbreak. *International Journal of Production Research, 58*(10), 2904–2915.

Ivanov, D., & Dolgui, A. (2021b). OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: Managerial insights and research implications. *International Journal of Production Economics, 232*, 107921.

Ivanov, D., & Rozhkov, M. (2020). 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, 291*(1–2), 387–407.

Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research, 57*(3), 829–846.

Kumar, S., Mookerjee, V., & Shubham, A. (2018). Research in operations management and information systems interface. *Production and Operations Management, 27*(11), 1893–1900.

Li, Y., Chen, K., Collignon, S., & Ivanov, D. (2021). Ripple effect in the supply chain network: Forward and backward disruption propagation, network health and firm vulnerability. *European Journal of Operational Research, 291*(3), 1117–1131.

Lohmer, J., Bugert, N., & Lasch, R. (2020). Analysis of resilience strategies and ripple effect in blockchain-coordinated supply chains: An agent-based simulation study. *International Journal of Production Economics, 228*, 107882.

Lücker, F., Chopra, S., & Seifert, R. W. (2021). Mitigating product shortage due to disruptions in multi-stage supply chains. *Production and Operations Management, 30*(4), 941–964.

MacCarthy, B. L., Blome, C., Olhager, J., Srai, J. S., & Zhao, X. (2016). Supply chain evolution – theory, concepts and science. *International Journal of Operations & Production Management, 36*(12), 1696–1718.

MacCarthy, B., & Ivanov, D. (2022). *Digital supply chain*. Elsevier.

Nguyen, S., Chen, P. S.-L., & Du, Y. (2021). Risk identification and modeling for blockchain-enabled container shipping. *International Journal of Physical Distribution and Logistics Management, 51*(2), 126–148.

Panetto, H., Iung, B., Ivanov, D., Weichhart, G., & Wang, X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control, 47*, 200–213.

Papadopoulos, T., Gunasekaran, A., Dubey, R., Altay, N., Childe, S. J., & Wamba, S. F. (2017). The role of Big Data in explaining disaster resilience in supply chains for sustainability. *Journal of Cleaner Production, 142*(2), 1108–1118.

Pavlov, A., Ivanov, D., Werner, F., Dolgui, A., & Sokolov, B. (2020). Integrated detection of disruption scenarios, the ripple effect dispersal and recovery paths in supply chains. *Annals of Operations Research*. https://doi.org/10.1007/s10479-019-03454-1

Pettit, T. J., Croxton, K. L., & Fiksel, J. (2019). The evolution of resilience in supply chain management: A retrospective on ensuring supply chain resilience. *Journal of Business Logistics, 40*(1), 56–65.

Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso Wamba, S. (2020). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03685-7

Queiroz, M. M., Telles, R., & Bonilla, S. H. (2019). Blockchain and supply chain management integration: A systematic review of the literature. *Supply Chain Management, 25*(2), 241–254.

Ralston, P., & Blackhurst, J. (2020). Industry 4.0 and resilience in the supply chain: A driver of capability enhancement or capability loss? *International Journal of Production Research, 58*(16), 5006–5019.

Roeck, D., Sternberg, H., & Hofmann, E. (2020). Distributed ledger technology in supply chains: A transaction cost perspective. *International Journal of Production Research, 58*(7), 2124–2141.

Rozhkov, M., Ivanov, D., Blackhurst, J., & Nair, A. (2022). Adapting supply chain operations in anticipation of and during the COVID-19 pandemic. *Omega, 110*, 102635.

Ruel, S., El Baz, J., Ivanov, D., & Das, A. (2021). Supply chain viability: Conceptualization, measurement, and nomological validation. *Annals of Operations Research*. https://doi.org/10.1007/s10479-021-03974-9

Sheffi, Y. (2015). Preparing for disruptions through early detection. *MIT Sloan Management Review, 57*, 31.

Sodhi, M., Tang, C., & Willenson, E. (2021). Research opportunities in preparing supply chains of essential goods for future pandemics. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2021.1884310

Sokolov, B., Ivanov, D., & Dolgui, A. (Eds.). (2020). *Scheduling in Industry 4.0 and cloud manufacturing*. Springer, ISBN 978-3-030-43176-1.

Tang, C. S., & Veelenturf, L. P. (2019). The strategic role of logistics in the Industry 4.0 era. *Transportation Research Part E: Logistics and Transportation Review, 129*, 1–11.

Waller, M. A., & Fawcett, S. E. (2013). Data science, predictive analytics, and big data: A revolution that will transform supply chain design and management. *Journal of Business Logistics, 34*(2), 77–84.

Wamba, S. F., & Queiroz, M. M. (2020). Industry 4.0 and the supply chain digitalisation: A blockchain diffusion perspective. *Production Planning & Control*, 1–18.

Winkelhaus, S., & Grosse, E. H. (2020). Logistics 4.0: A systematic review towards a new logistics system. *International Journal of Production Research, 58*(1), 18–43.

Yang, H., Kumara, S., Bukkapatnam, S. T. S., & Tsung, F. (2019). The internet of things for smart manufacturing: A review. *IISE Transactions, 51*(11), 1190–1216.

Yoon, J., Talluri, S., & Rosales, C. (2020). Procurement decisions and information sharing under multi-tier disruption risk in a supply chain. *International Journal of Production Research, 58*(5), 1362–1383.

Zouari, D., Ruel, S., & Viale, L. (2021). Does digitalising the supply chain contribute to its resilience? *International Journal of Physical Distribution and Logistics Management, 51*(2), 149–180.

Internet Links:

Adelhardt, D. (2020). *SupplyOn Blog: "How to better copy with demand volatility"*. Accessed March 04, 2021, from https://www.supplyon.com/en/blog/how-to-better-cope-with-demand-volatility/

Kastl, C. (2020). *SupplyOn Blog: "Visibility, Analytics & Intelligence: Get full transparency on your supply chain, not just in times of crisis!"*.

Reng, K. (2020). *SupplyOn Blog: "How to ensure a supply chain's mid- and long-term resilience—including practical examples"*.

SupplyOn. (2022). Accessed August 08, 2022, from https://www.supplyon.com/en/

Xiao, Y. (2020). *SupplyOn Blog: "The art of manufacturing electronic vehicles: Seres Automobile lays the foundation for its supply chain together with SupplyOn"*. SupplyOn (2021). Accessed March 04, 2021, from https://www.supplyon.com/en/blog/manufacturing-electronic-vehicles-seres-automobile-lays-supply-chain-foundation-via-supplyon/