OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: Managerial insights and research implications

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OR Methodologies and Managerial Insights for Coping with Disruption Propagations in Supply Chains Amid the COVID-19 and Withstanding Future Pandemics

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Abstract

The COVID-19 pandemic unveils unforeseen and unprecedented fragilities of the supply chains (SC). One strong stressor to SCs and their numerous collapses comes from disruption propagations through the networks. The existing knowledge in modelling disruption propagations in SCs is multi-faceted and deserves to be analysed for the unique set of factors shaping SC adaptations during and after a global pandemic. We scrutinize OR studies published in international journals and dealing with disruption propagation in SCs. This streamlining of the literature allowed revealing several new research tensions and novel categorizations/classifications. Our study pursues two major contributions subject to two research questions. First, we collate the state-of-the-art in research on disruption propagations in SCs and identify a methodical taxonomy and theories displaying the value and applications of OR methods to coping with pandemic impacts on the SCs. Second, we reveal and systemize managerial insights from the theory that can be used for operating (adapting) amid a pandemic and at the times of recovery along with withstanding future pandemics. In particular, we find that outcomes of the OR contributions and the resulting managerial insights can be categorized into three levels, i.e., network, process, and control. Our outcomes in both managerial and theoretical domains are structured into five stages (i.e., Anticipation; Early detection; Containment; Control and Mitigation; and Elimination) following the WHO classification. Our study can be used by industry and researchers alike in order to progress the decision-support systems guiding the SCs amid the COVID-19 pandemic and recovering them thereafter. Suggestions for future research directions are offered and discussed.

Keywords: supply chain; COVID-19; pandemic; disruption propagation; ripple effect; structural dynamics; recovery; managerial insights

1. Introduction

COVID-19 was first reported in late 2019 in Wuhan, China. By May 4, 2020, over 2.4 million people were infected and approximately 240,000 people died. The COVID-19 pandemic has created a lot of uncertainty in all areas of life and in supply chains (SC) in particular. SCs experience unprecedented vulnerabilities in lead-times and order quantities, disruptions in networks structures, and severe demand fluctuations. Adversely, many of these vulnerabilities are encountered simultaneously. 94% of the Fortune 1000 companies have been reported seeing coronavirus-driven SC disruptions (Fortune 2020). A recent survey by ISM of about 600 US companies revealed that in the mid of April 2020, average lead times were at least twice as long as compared to "normal" operations, for Asian (222% for China, 217% for Korea, and 209% for Japan), European (201%) and domestically sourced inputs (200%) (ISM 2020). The same

report says that Chinese and European manufacturing is at about one-half normal capacity, 53% and 50% respectively.

The outbreak of COVID-19 virus and an associated global pandemic have shed light on the scope and scale of the ripple effect seen in disruption propagations in the global SCs (Ivanov et al. 2014a; Dolgui et al. 2018). Haren and Simchi-Levi (2020) observed two examples of the COVID-19-triggered ripple effect immediately after the epidemic outbreak. Fiat Chrysler Automobiles NV was halting production at a car factory in Serbia, because it can't get parts from China. Hyundai "*decided to suspend its production lines from operating at its plants in Korea ... due to disruptions in the supply of parts resulting from the coronavirus outbreak in China.*" While these observations were done in the second half of February 2020, the scaling of the ripple effects in March-May 2020 have been exponential, driven by the closures of manufacturing facilities, stores and logistics activities and adversely affecting almost all industries and services worldwide (Choi et al. 2020; Choi 2020, Ivanov 2020; Ni et al. 2020). The World Economic Forum - WEF (2020) emphasized the need for firms and organizations to adapt their SCs amid the COVID19 pandemic and in light of future trade challenges. In its totality, the COVID-19 pandemic seriously wreaks havoc on SCs and poses a series of novel decision-making settings for SC professionals and novel questions for researchers which are relevant amid the pandemic and in the course of future recoveries.

Operational Research (OR) community possessыu an enormous scope of methods and tools that can be used for decision-making support under uncertainty. In particular, advanced modelling approaches have been established for decision-making environments with uncertain supply quantities and lead-times (Prak et al. 2017), supplier and facility disruptions (Snyder and Daskin 2005, Klibi and Martel 2012, Qi 2013, Paul et al. 2014, Silbermayr and Minner 2016), transportation uncertainties (Amiri-Aref et al. 2019), and demand uncertainties (Rezapour et al. 2017, Amiri-Aref et al. 2018, Mohamed et al. 2020). We refer to comprehensive surveys on these operational and disruption risks (Klibi et al. 2010, Snyder et al. 2016, Govindan et al. 2017, Shen and Li 2017, Hosseini et al. 2019). Alike literature on epidemics and humanitarian disasters with SC and logistics context delivers a rich body of inspiring methods and outcomes (Altay and Green 2006, Van Wassenhove 2006, Dasaklis et al. 2012, Gupta et al. 2016, Dubey et al. 2019, Besiou and van Wassenhove 2020).

Our study is devoted to one specific and strong stressor to SCs during a pandemic – the disruption propagations through the networks (i.e., the ripple effect) and the subsequent changes in the SC structures (i.e., structural dynamics). Adversely, SC disruptions are stimulated by simultaneous disruptions and uncertainties in demand and supply. The existing knowledge in modelling the SC ripple effect and structural dynamics is multi-faceted and deserves to be analysed for the unique set of factors shaping SC adaptations when facing a global pandemic.

We scrutinize 40 quantitative studies published in 15 international journals (cf. Appendix 1) and dealing with disruption propagation and structural dynamics in SCs. This streamlining of the literature allowed revealing several new research tensions and novel categorizations/classifications. To this end, our study pursues to address two central research questions (RQ):

RQ1: How did the OR literature address issues related to the ripple effects and structural dynamics in SCs in terms of methodologies, problem settings, outcomes and managerial insights?

RQ2: How the existing OR knowledge can be used to support the SC managers in adapting the supply networks amid the COVID-19 pandemic and what are future research opportunities?

In particular, we find that outcomes of the OR contributions and the resulting managerial insights can be categorized into three levels, i.e., network, process, and control. Our outcomes in both managerial and theoretical domains are structured into five stages (i.e., Anticipation, Early detection, Containment, Control and Mitigation, and Elimination) following the WHO classification. Our study can be used by industry and researchers alike in order to progress the decision-support systems guiding the SCs amid the COVID-19 pandemic and recovering them thereafter. Suggestions for future research directions are offered and discussed.

The rest of this study is organized as follows. In section, we presented methodic of our study. Section 3 is devoted to analysis of OR theories, applications and managerial insights. In Section 4, we organize the discussion around an extrapolation of the existing knowledge on pandemic settings. We discuss both managerial implications and future research angles. We conclude the paper in Section 5 by summarizing this study.

2. Methodic of our study

2.1. Purpose of our study

SC disruptions have become a visible research avenue over the last two decades. In several settings, disruptions can be localized without cascading through a network. Though, in other situations upstream disruptions are propagating downstream the SCs adversely impacting performance of individual firms and overall networks. According to Dolgui et al. (2020), the ripple effect "refers to structural dynamics and describes a downstream propagation of the downscaling in demand fulfilment in the supply chain (SC) as a result of a severe disruption." Ivanov et al. (2014b) state that "*Ripple effect describes the impact of a disruption on SC performance and disruption-based scope of changes in the SC structures and parameters*". These definitions imply that the ripple effect is concerned with multi-stage networks and triggering failures in the network elements as a domino effect.

In 2010-2014, first studies appeared in the area of the ripple effect and an increased interest in disruption propagation and correlated disruptions has been observed (Liberatore et al. 2012, Mizgier et al. 2012, Ghandge et al. 2013, Ivanov et al. 2014a). The first explicit definition of the ripple effect has been undertaken by Ivanov et al. (2014b) as indicated above. Thus far, much progress has been done in this area deploying different methodologies and obtaining relevant managerial outcomes and recommendations (Scheibe and Blackhurst 2018). Dolgui et al. (2018) and Mishra et al. (2019) reviewed progress in the ripple effect research for the last years mostly focusing on classifications of the resilience aspects and risk type categorization. However, there is no published survey comprehensively encompassing the disruption propagations in SCs and the resulting structural dynamics from the OR methodology point of view.

Our study pursues two contributions. First, we collate the state-of-the-art in the research on SC ripple effect and structural dynamics and identify a methodical taxonomy and theories displaying the value and applications of OR methods to coping with pandemic impacts on the SCs. Second, we reveal and systemize managerial insights from the theory that can be used for recovery from the COVID-19 and withstanding future pandemics.

2.2. Literature selection process

The literature for analysis of recent methodical contributions to managing the ripple effect has been selected based on a thorough authors' work in the ripple effect area for the last decade and observing the relevant publications along with editing several related special issues in prestigious international journals. This selection was supported by a supplementing search in most common databases (e.g., Scopus Database, ScienceDirect (Elsevier), Emeraldinsight (Emerald), Wiley Online Library (Wiley), Taylor & Francis Online (Taylor & Francis), Springer Link (Springer), and Informs PubsOnline according to the following protocol (on the example of SCOPUS):

(*supply* AND *chain* AND *disruption*) AND (*ripple*) OR (*cascade*) OR (*cascading*) OR (*propagation*) OR (*correlated* AND *disruption*) OR (*structural* AND *dynamics*) OR (*transmission*)

In total, we obtained a list of 142 journal papers in the areas of operational and supply chain research that have been manually processed and narrowed to meet the scope and scale of our analysis. We do not claim that the literature analysed in this paper is a full collection of all most influential contributions; though we believe to be very close to this setting. We underline that we do not follow classical structured literature review scheme but rather analyse most representative studies in terms of theoretical tensions and managerial applications. The details of our literature review protocol are given in Fig. 1.

 [Insert Fig. 1 here]

We followed five major inclusion criteria. The search has been performed on May 2, 2020; the papers published by this date in international peer-reviewed journals have been included. We considered only papers with SC topics related to keywords „ripple effect", „disruption propagation", „cascading", „structural dynamics". Moreover, we restricted ourselves to the papers utilizing OR methods (e.g., empirical studies have not been analysed). Further, we considered only papers that clearly display the mechanisms of disruption propagations. In particular, we excluded papers on two-echelon problems since a meaningful disruption propagation can be treated in the setting with three echelons as a minimal complexity level. Finally, the papers without or with insufficient information about managerial insights have not been included.

3. OR theories, major outcomes and managerial insights

3.1. Methodical perspectives

Our analysis revealed numerous OR theories that have been successfully applied to the SC problems with disruption propagations (Table 1)

[Insert Table 1 here]

We found applications of the following OR theories and methods (in alphabetical order): Agent-Based Simulation; Bayesian Networks; Complexity theory; Discrete-Event Simulation; Entropy Analysis; Graph theory; Linear / Mixed-Integer Programming; Markov Chains; Monte-Carlo Simulation; Optimal Control; Petri Nets; Reliability Theory; Robust Optimization; Statistical Analysis; Stochastic Optimization; and Systems Dynamics. The highest number of publications can be seen in mixed-integer and linear programming and Bayesian networks (6 papers

respectively), optimal control, complexity and graph theories (5 papers respectively), reliability theory and discrete-event simulation (4 papers respectively).

When aggregating different methods at a larger scale, the largest number of studies can be observed in the area of network and complexity theories (24 papers); with regards to mathematical optimization 11 papers in total can be observed; simulation studies count to 8 papers, and 5 papers are related to control theory.

Analysis of such aggregated categories lead us to a proposition to classify the existing studies into three levels, i.e., network level, process level, and control level. Such a classification appeared to be logical and convenient to develop further categorizations of main outcomes, managerial insights and future research directions. We considered the following criteria to articulate the differences between the network, process, and control levels. The network level is characterized by a macro-view on SC structures and disruption propagations focusing on the structural properties and relations. This level does operate in terms of networks and graphs from a much generalized perspective of structures and does not consider operational parameters. These parameters are in the scope of the process level which organizes the debate around the parametrized structures to balance demands, processing capacities, and supply. Typical problems at the process level are related to production-distribution planning in terms of flow optimization. Though, these models do not go into details of inventory control and production-ordering policies which are accommodated at the control level.

3.2. Major outcomes and managerial insights

Now we are drawing the reader's attention towards the analysis of major outcomes and managerial insights. A detailed paper-by-paper analysis is offered in Table 2.

[Insert Table 2 here]

Table 2 summarizes the titles, authors, journals, central research questions, methods and outcomes & managerial insights of each paper analysed. We focus now on major outcomes and managerial insights and generalize the insights from individual paper analyses at an aggregated scale according to the previously introduced classification into the network (N), process (P), and control (C) levels. The major outcomes and managerial insights that can be deduced from the existing OR studies are categorized and presented in Table 3.

[Insert Table 3 here]

The detailed analysis follows.

3.2.1. Network level

The studies at the network level are mostly looking at unlocking associations between network structures and risk propagations (Li et al. 2019). For example, Basole and Bellamy (2014) show that small-world supply network topologies (i.e., networks where each node is connected to several of its neighbors and a few distant nodes) consistently outperform supply networks with scale-free characteristics (networks where nodes are connected to a few other nodes, while a small number of nodes are connected to many other nodes). The network- and graph-theoretic studies allow to understand potential weaknesses in the SC designs taking into account the structure, connectivity, and dependence within the SC (Blackhurst et al. 2018). An important contribution can be seen in detecting disruption scenarios and identifying critical nodes (or combinations of nodes) the failure of which would lead to SC discontinuities and operations collapses (Zeng and Xiao 2014, Tang et al. 2016, Deng et al. 2019, Pavlov et al. 2020). Another

important application area is measuring of the SC robustness and resilience under disruption propagations and structural dynamics (Han and Shin 2016, Sokolov et al. 2016, Hosseini and Ivanov 2019, Li and Zobel 2020). Along with the stress-testing of the existing SC designs, the network level analyses suggest directions to enhance the resilience, e.g., through supplier diversifications (Lei et al. 2020). Episodically, the issues beyond the mere economic performance such as sustainability have been examined (Levner and Ptuskin 2018). Moreover, the macro-problems of SC economies such as bankruptcies of suppliers (Mizgier et al. 2012) and retail dynamics (Osadchiy et al. 2016) have been studied. The studies with the use of Bayesian networks allow to model dependencies and inter-dependencies in supply networks; moreover, the robustness and resilience analyses with consideration of both vulnerabilities and recovery become possible (Garvey et al. 2015, Ojha et al. 2018, Cao et al. 2019). An integration of Markov chains into the Bayesian networks enables an additional and valuable contribution, i.e., to model the node's behaviors along with the overall network dynamics (Hosseini et al. 2019).

3.2.2. Process level

The studies at the process level are positioned at a less generalized perspective as compared to the network level. These studies build upon parametrized structures to balance demands, processing capacities, and supply. Production-distribution planning in terms of flow optimization under disruption propagation and structural dynamics is the focus of the process level analysis. The analysis at the process level is mostly grounded in mathematical optimization and system dynamics simulation.

The process level studies help to analyse measures for disruption propagation mitigation. The mathematical optimization studies are usually organized around an SC design which may vary structurally and parametrically over time and optimize flow reconfigurations under disruption propagation. For example, Bueno-Solano and Cedillo-Campos (2014) show that protective measures against the ripple effect can drastically increase the inventory levels in the SC. Garvey and Carnovale (2020) argue that "*managers should focus more of their attention on control or mitigation of exogenous events [...], and spend less of an effort and resources on mitigating the propagation of exogenous risk.*". Ghadge et al. (2013) show how systems dynamics simulation can help in prediction of potential failure points in the SC along with the overall impact of the ripple effect on the performance. Details differ across the studies but most of them share a common set of outcomes and managerial insights such as joint optimisation of SC capacities and recovery capabilities for new and existing SCs; trade-offs between investments in increased recovery capability and redundant capacity provision; decision-making support on safety stock management, reconfiguration of production and inventory plans after disruptions, and recovery scheduling (Ivanov et al. 2015, Sinha et al. 2019, Goldbeck et al. 2020). As the most desired outcome, process level analysis seeks to identify and test resilient SC designs to sustain disruptions which range from optimistic and pessimistic scenarios (Ivanov et al. 2014), probability-based disruptions (Pariazar et al. 2017) to worst-cases in robust optimization (Zhao and Freeman 2019, Özçelik et al. 2020). In some settings, the authors solve inverse problems and search for elements in the SC structures that should be strengthened to withstand the disruption propagations (Liberatore et al. 2012, Pavlov et al. 2013). Some extensions can be seen in including the recovery costs (Ivanov et al. 2016) and sustainability issues (Pavlov et al. 2019).

3.2.3. Control level

The studies at the control level are distinctively characterized by inclusion of details of inventory control and production-ordering policies into the analysis. At this level, simulation methods dominate. They allow analyzing dynamic SC behaviors and time-dependencies in disruption propagations and responses. One interesting observation from these studies is an insight about "disruption tails". Several works (Ivanov 2019, Dolgui et al. 2020) observed that non-coordinated ordering and production policies during a disruption period may result in backlog and delayed orders, the accumulation of which causes post-disruption SC instability, resulting in further delivery delays and non-recovery of SC performance. These residues have been named "disruption tails". The extant literature suggests that specific "revival" policies must be developed for the transition from the recovery to the disruption-free operations mode to avoid the "disruption tails". Interestingly, the first research work on the impacts of COVID-19 pandemic on the SC has utilized the simulation methodology revealing several unique features which make the pandemic a specific and very severe risk type for SCs (Ivanov 2020a).

4. Directions for managerial applications and future research in the pandemic settings

In this section, we focus on the articulation of the state-of-the-art knowledge in OR about the disruption propagations and structural dynamics for a pandemic setting. In particular, we extrapolate the outcomes and managerial insights revealed in Section 3 on the COVID-19 pandemic and elaborate on future research directions (Table 4).

[Insert Table 4 here]

Our analyses of outcomes in both managerial and theoretical domains in Table 4 are structured into five stages (i.e., Anticipation; Early detection; Containment; Control and Mitigation; and Elimination) following the WHO classification (WHO 2018).

4.1. Anticipation and early detection

The pandemic cycle usually begins with the stage of anticipation and early detection. At this stage, SCs should keep an eye out and enable preparedness measures. The OR methods can help in a number of areas such how to identify critical scenarios of disruption propagations according to an epidemic outbreak dynamics and forecast the impact of possible propagating disruptions on SC performance. Moreover, OR theories can be efficiently used to predict the time periods during which the SCs can sustain the disruption propagations and survive despite the discontinuities, identify critical suppliers and facilities for maintaining SC operations, and select and fortify SC designs to sustain epidemic outbreaks. Overall, the decision on the anticipation and early detection stage target at implementing of "Design-for-Resilience" network structures.

Nonetheless, further research directions arise for OR community in light of pandemic settings. There are crucial opportunities to develop theories and models for disruption propagation analysis in supply networks with specific consideration of pandemics, to visualize the ripple effect and structural dynamics, and to extend towards a multi-categorical analysis spanning dimensions of resilience and sustainability. Moreover, researchers can examine new analysis categories such as network viability (Ivanov and Dolgui 2020, Ivanov 2020). Another important direction is to investigate the data analytics and digital technology capabilities to early detect the disruption propagations following epidemic outbreaks.

4.2. Containment

At the containment stage, the environment becomes increasingly vulnerable followed by quarantine times, interruptions of logistics due to variations in containment timing and scaling in different geographical areas, and some lock-downs. At this stage, SCs are experiencing first misbalances of supply and demand due to longer-lead times, demand drops and supply unavailability due to facility closures. OR methods can support SC managers at this stage by stress-testing of the existing and alternative SC configurations and production-distribution plans for some scenarios of structural dynamics in anticipation of or as a reaction to facility/market closure due to quarantines and lock-downs. OR methods can also help optimise contingency / preparedness plans for their efficient and timely deployment under different scenarios of epidemic propagation.

The new research opportunities for OR community are very rich for the containment pandemic stage. For example, there is an urgent need to examine new understandings, theories, and novel approaches concerning SC preparedness and disruption mitigation during the beginning epidemic outbreaks. This can help articulate antecedents, drivers, and economic and social performance implications of simultaneous disruption and epidemic propagations. One specific and underexplored are is re-designing of the SCs for production switches to unusual products (e.g., mask production at car manufacturers).

4.3. Control and mitigation

Amid the control and mitigation stage, SCs need to adapt to a "new normal" and start preparing for a recovery. For example, OR models can help to identify the balanced levels of capacity utilization and production rates at different firms in the SC to achieve maximum possible performance. It is now very relevant to COVID-19 pandemic since the SCs are misbalanced and it is difficult to decide at which level of capacity the firms should start with and scale during a recovery thereafter. The OR models can help identify the optimal material flows in a multi-period mode when the SC structures change through these periods. This is very relevant to modeling the SC flows amid a pandemic and during a recovery. Another relevant issue is consideration of backlog accumulations over the disruption time which can become a major driver of disruption propagations during the production and logistics ramp-up activities. At the control and mitigation stage, the role of digital twins is increasing since SC visibility and information coordination are the key capabilities to cope with the ripple effect. OR methods can help analyse the impacts of disruption propagation in dynamics with adaptations of ordering, production and inventory control policies and to simulate operations policies amid a pandemic. Moreover, OR theories can be used to explore re-allocations of supply and demand during a pandemic given simultaneous disruptions in upstream and markets. In addition, OR methods can be applied to propose recovery plans along with analysis of timing and scaling of facility/market closures and openings in different geographical regions.

As for future research, we point to the opportunities for substantial contributions to develop and examine digital SC twins to map the network elements and adapt the SCs according to disruption propagations and structural dynamics. Another promising research direction is to explore the role of timing and scaling of the production and logistics ramp-ups after the quarantines and lock-down eliminations.

4.4. Elimination or eradication

Exiting a pandemic can be even more challenging as stepping inside. During the elimination stage, the SCs need to be recovered and adapted to new, post-pandemic realities. OR methods can help incorporate after-pandemic environments in the re-designing of the SCs. OR can also be of value to examine the existing and potential SC configurations under post-pandemic conditions in the supply base and the markets. Furthermore, OR techniques can be used to analyse the "disruption tails" and long-term stabilization of production-inventory systems.

The elimination stage contains a variety of novel research problem settings. For example, there is a research gap in how to find optimal scaling and timing of production and logistics ramp-ups during the "exit" after the lock-downs. It is also a timely and crucial issue to examine SC re-design methods for sever structural changes in supply and demand after a pandemic (e.g., supplier bankruptcies and demand drops/shifts). Finally, we point to the needs to explore the concept of SC viability as a long-term maintaining of survivability under different and ever changing environmental conditions.

4.5. Note on a danger of jeopardizing SC resilience models for the pandemic settings

Undoubtedly, OR knowledge in SC disruption risks and resilience will be the leading perspective guiding researchers and industry leaders alike through the pandemic and a recovery thereafter. With that being said, there is a danger of jeopardizing SC resilience models for the pandemic settings. OR community has developed a mature body of literature on coping with different types of disruption risks. A pandemic is one specific type of disruption risks and it has quite unique implications for SCs which are not encountered in other types of SC disruptions. In contrast to geographically centered natural/industrial disasters with singular occurrence, a pandemic is not limited to a particular region or confined to a particular time period (Ivanov and Das 2020). Different SC components are affected sequentially or concurrently – manufacturing, DCs, logistics, and markets can become paralyzed within subsequent or overlapping time frames. Pandemic causes long-term disruption existence and its unpredictable scaling. Other specific issues are simultaneous disruption propagation (i.e., the ripple effect) and epidemic outbreak propagation, and simultaneous severe disruptions in supply, demand, and logistics infrastructure (Ivanov 2020a). Under pandemic conditions, it might be difficult to directly apply the most know SC resilience mechanisms such as risk mitigation inventories, subcontracting capacities, or backup supply and transportation infrastructures. As such, the studies on SC resilience should explicitly present pandemic-specific settings to be classified as a contribution to adapt through the pandemic and recover. Otherwise, literally each study on supply disruptions can be adapted to the pandemic background which is fundamentally wrong.

5. Conclusions

The COVID-19 pandemic unveils fragility of the SCs at an unforeseen scale. One specific and strong stressor to SCs amid a pandemic and during the post-pandemic recoveries comes from the disruption propagations through the networks (i.e., the ripple effect) and the subsequent changes in the SC structures (i.e., structural dynamics).

This paper deduced managerial implications from the existing OR literature on disruption propagations in SC and revealed future research directions. We collated for the first time the existing OR knowledge in modelling the SC ripple effect and structural dynamics. We believe that such

an overview would be useful for industry leaders and researchers alike shaping SC adaptations during and after a global pandemic. On one hand, we collated the state-of-the-art in the research on SC disruption propagation and identified a methodical taxonomy. On the other hand, we revealed and systemized managerial insights from the theory that can be used for recovery from the COVID-19 and withstanding future pandemics. These results can be used by industry and researchers alike in order to progress the decision-support systems guiding the SCs amid the COVID-19 pandemic and recovering them thereafter.

In particular, we found that outcomes of the OR contributions and the resulting managerial insights can be categorized into three levels, i.e., network, process, and control. Our outcomes in both managerial and theoretical domains are structured into five stages (i.e., Anticipation; Early detection; Containment; Control and Mitigation; and Elimination) following the WHO classification.

Limitations exist, as with any study. We have narrowed our analysis on the disruption propagation literature related to commercial SCs. Obviously, a rich variety of knowledge in the area of humanitarian logistics and SCs can enrich the findings of our study. We also do not pretend to be encyclopedic; we assume that some relevant studies might have not been uncovered and remained outside of our review.

As for future research, we pointed numerous opportunities for substantial contributions to develop and test new theories, models, and resilience mechanisms for control and mitigation of disruption propagation in SCs with specific consideration of pandemic features, such as:

- long-term disruption existence and its unpredictable scaling;
- simultaneous disruption propagation and epidemic outbreak propagation;
- simultaneous severe disruptions in supply, demand, and logistics infrastructure

We hope that the novel systematizations/categorizations proposed in this study will be of value for researchers and practitioners alike in guiding the SCs through the pandemic times and preparing them for recovery thereafter. Along with the constructed generalized perspectives, our study can be of value for researchers and industry professional alike to cope with the existing COVID-19 pandemic, recover thereafter, and most importantly to create a valuable reference source for future pandemics or pandemic-like disruptions.

References

Altay, N., Green, W.G. (2006). OR/MS research in disaster operations management. European Journal of Operational Research, 175(1),475–493.

Amiri-Aref, M., RZ Farahani, M, Hewitt, W, Klibi (2019). Equitable location of facilities in a region with probabilistic barriers to travel. Transportation Research Part E: Logistics and Transportation Review 127, 66-85.

Amiri-Aref, M., W, Klibi, MZ Babai (2018) The multi-sourcing location inventory problem with stochastic demand. European Journal of Operational Research 266 (1), 72-87.

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.

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

Besiou, M., LN Van Wassenhove (2020). Humanitarian operations: A world of opportunity for relevant and impactful research. Manufacturing & Service Operations Management 22 (1), 135-145.

Bueno-Solano, A., Cedillo-Campos, M.G. (2014). Dynamic impact on global supply chains performance of disruptions propagation produced by terrorist acts. Transportation Research Part E: Logistics and Transportation Review, 61, pp. 1-12

Cao, S., Bryceson, K., Hine, D. (2019). An Ontology-based Bayesian network modelling for supply chain risk propagation. Industrial Management and Data Systems, 119(8), 1691-1711

Chaudhuri, A., Srivastava, S.K., Srivastava, R.K., Parveen, Z. (2016). Risk propagation and its impact on performance in food processing supply chain: A fuzzy interpretive structural modeling based approach. Journal of Modelling in Management, 11(2), 660-693

Choi TY, Rogers D, Vakil B. (2020). Coronavirus is a Wake-Up Call for Supply Chain Management. Harvard Business Review, March 27th.

Choi, T.-M. (2020). Innovative "Bring-Service-Near-Your-Home" Operations under Corona-Virus (COVID-19/SARS-CoV-2) Outbreak: Can Logistics Become the Messiah? *Transportation Research Part E: Logistics and Transportation*, forthcoming

Dasaklis, T. K., Pappis, C. P., & Rachaniotis, N. P. (2012). Epidemics control and logistics operations: A review. International Journal of Production Economics, 139(2), 393–410.

Deng, X., Yang, X., Zhang, Y., Li, Y., Lu, Z. (2019). Risk propagation mechanisms and risk management strategies for a sustainable perishable products supply chain. Computers and Industrial Engineering 135, 1175-1187.

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.

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.

Dubey, R., Gunasekaran, A., & Papadopoulos, T. (2019d). Disaster relief operations: past, present and future. Annals of Operations Research, 283(1-2), 1-4.

Farahani, R.Z., Lotfi, M.M., Rezapour, S. (2020). Mass Casualty Management in Disaster Scene: A Systematic Review of OR&MS research in Humanitarian Operations. European Journal of Operational Research, DOI: 10.1016/j.ejor.2020.03.005

Fortune (2020). https://fortune.com/2020/02/21/fortune-1000-coronavirus-china-supply-chain-impact/, accessed on March 10, 2020

Garvey, M.D., Carnovale, S. (2020). The Rippled Newsvendor: A New Inventory Framework for Modelling Supply Chain Risk Severity In The Presence of Risk Propagation. International Journal of Production Economics, forthcoming.

Garvey, M.D., Carnovale, S., Yeniyurt, S. (2015). An analytical framework for supply network risk propagation: A Bayesian network approach. European Journal of Operational Research, 243 (2): 618-627.

Ghadge, A., Dani, S., Chester, M., & Kalawsky, R. (2013). A systems thinking approach for modelling supply chain risk propagation. Supply Chain Management: An International Journal, 18(5), 523–538.

Govindan, K., Fattahi, M., Keyvanshokooh, E., (2017). Supply chain network design under uncertainty: A comprehensive review and future research directions. European Journal of Operational Research 263, 108–141.

Gupta, S., Starr, M., Zanjirani Farahani, R. and Matinrad, N. (2016) Disaster management from a POM perspective: mapping a new domain. Production and Operations Management 25(10) 1611–1637.

Haren, P., D. Simchi-Levi (2020). How Coronavirus Could Impact the Global Supply Chain by Mid-March. Harward Business Review, February 28, 2020, https://hbr.org/2020/02/how-coronavirus-could-impact-the-global-supply-chain-by-mid-march?ab=hero-subleft-1, accessed on March 10, 2020

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

Hosseini S., Ivanov D. (2019). Resilience Assessment of Supply Networks with Disruption Propagation Considerations: A Bayesian Network Approach, Annals of Operations Research, DOI: 10.1007/s10479-019-03350-8

Hosseini S., Ivanov D., Dolgui A. (2019). Ripple effect modeling of supplier disruption: Integrated Markov Chain and Dynamic Bayesian Network Approach. International Journal of Production Research, in press.

Hosseini S., Ivanov D., Dolgui A. (2019). Review of quantitative methods for supply chain resilience analysis. Transportation Research: Part E, 125, 285-307.

ISM (2020). https://weareism.org/coronavirus-ism.html. Accessed on May 4, 2020.

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, https://doi.org/10.1080/00207543.2020.1750727

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.

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

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

Ivanov, D., Dolgui A., Sokolov B. (Eds) (2019). Handbook of Ripple Effects in the Supply Chain. Springer, New York,

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

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

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

Ivanov, D., Sokolov, B., Hartl, R., Dolgui, A., Pavlov, A., Solovyeva, I. (2015). Integration of aggregate distribution and dynamic transportation planning in a supply chain with capacity disruptions and ripple effect considerations. International Journal of Production Research, 53(23), 6963-6979.

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

Ivanov, D., 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), 2010, pp. 409-420.

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

Ivanov, D., & Das, A. (2020). Coronavirus (COVID-19 / SARS-CoV-2) and supply chain resilience: A research note. *International Journal of Integrated Supply Management*, (Forthcoming).

Klibi, W., A. Martel (2012). Scenario-based supply chain network risk modeling. European Journal of Operational Research 223 (3), 644-658.

Klibi, W., A. Martel, and A. Guitouni. (2010). The design of robust value-creating supply chain networks: A critical review. European Journal of Operational Research 203(2): 283–293.

Lei, Z., Lim, MK., Cui L. & Y. Wang (2020). Modelling of risk transmission and control strategy in the transnational supply chain. International Journal of Production Research.
Pages: 1-20 | DOI: 10.1080/00207543.2019.1698782

Levner E., Ptuskin A. (2018). Entropy-based model for the ripple effect: managing environmental risks in supply chains. International Journal of Production Research, 56(7), 2539-2551.

Li, Y., Zobel, C. W. (2020). Exploring Supply Chain Network Resilience in the Presence of the Ripple Effect, International Journal of Production Economics, forthcoming

Li, Y., Zobel, C. W., Seref, O., and Chatfield, D. C. (2019). Network Characteristics and Supply Chain Resilience under Conditions of Risk Propagation. International Journal of Production Economics

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

Lu, M., Ran, L., Shen, Z.-J.M. (2015) Reliable facility location design under uncertain correlated disruptions. Manufacturing & Service Operations Management, 17(4), 445-455.

Mishra, D., Dwivedi, Y., Rana, N., Hassini, E. (2019). Evolution of supply chain ripple effect: a bibliometric and meta-analytic view of the constructs. International Journal of Production Research, DOI: https://doi.org/10.1080/00207543.2019.1668073

Mizgier, K.J., Jüttner, M.P., Wagner, S.M. (2013). Bottleneck identification in supply chain networks. International Journal of Production Research 51(5), 1477-1490

Mohamed, IB., W Klibi, F Vanderbeck (2020. Designing a two-echelon distribution network under demand uncertainty. European Journal of Operational Research 280 (1), 102-123

Ni, J. (2020). How China can rebuild global supply chain resilience after COVID-19. https://www.weforum.org/agenda/2020/03/coronavirus-and-global-supply-chains/, accessed on April 4, 2020

Ojha, R., Ghadge, A., Tiwari, M.K., Bititci, U.S. (2018). Bayesian network modelling for supply chain risk propagation. International Journal of Production Research, 56(17), 5795-5819.

Osadchiy, N., Gaur, V., Seshadri, S. (2016). Systematic risk in supply chain networks. Management Science, 62(6), 1755-1777.

Özçelik, G., Ö. F. Yılmaz & F. B. Yeni (2020). Robust optimisation for ripple effect on reverse supply chain: an industrial case study. International Journal of Production Research,
DOI: 10.1080/00207543.2020.1740348

Pariazar, M., Root, S., Sir, M.Y. (2017). Supply chain design considering correlated failures and inspection in pharmaceutical and food supply chains. Computers and Industrial Engineering, 111, 123-138.

Park D., Teunter R., Syntetos A. (2017). On the calculation of safety stocks when demand is forecasted. European Journal of Operational Research, 256(1), 454-461

Paul, S.K., R. Sarker, and D. Essam. (2014). Real time disruption management for a two-stage batch production–inventory system with reliability considerations. European Journal of Operational Research 237, 113–128.

Pavlov A., Ivanov D., Pavlov D., Slinko A. (2019). Optimization of network redundancy and contingency planning in sustainable and resilient supply chain resource management under conditions of structural dynamics, Annals of Operations Research, DOI: 10.1007/s10479-019-03182-6

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, DOI:10.1007/s10479-019-03454-1.

Qi, L. (2013). A continuous-review inventory model with random disruptions at the primary supplier. European Journal of Operational Research 225(1): 59–74.

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

Scheibe K.P., Blackhurst, J. (2018). Supply chain disruption propagation: a systemic risk and normal accident theory perspective. International Journal of Production Research, 56(1-2), 43-59.

Shen B., Li Q. (2017). Market disruptions in supply chains: a review of operational models. Intl. Trans. in Op. Res. 24, 697–711

Silbermayr, L., S. Minner (2016). Dual sourcing under disruption risk and cost improvement through learning. European Journal of Operational Research 250 (1), 226-238

Sinha, P., Kumar, S., Prakash S. (2019). Measuring and Mitigating the Effects of Cost Disturbance Propagation in Multi-Echelon Apparel Supply Chains. European Journal of Operational Research, DOI: https://doi.org/10.1016/j.ejor.2019.09.015

Snyder, L V., Zümbül A., Peng P., Ying R., A. J. Schmitt, and B. Sinsoysal (2016). OR/MS Models for Supply Chain Disruptions: A Review. IIE Transactions, 48(2), 89-109.

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

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

Swierczek, A. (2014). The impact of supply chain integration on the 'snowball effect' in the transmission of disruptions: An empirical evaluation of the model. International Journal of Production Economics, 157, pp 89-104.

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

Van Wassenhove, L. N. (2006) Humanitarian aid logistics: Supply chain management in high gear. Journal of Operational Research Society 57 475–489.

World Health Organization (WHO) (2018) Managing epidemics: The key facts about major deadly disease, Available online on https://www.who.int/emergencies/diseases/managing-epidemics-interactive.pdf, last visit on 2 May 2020.

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

Zhao M., Freeman, N.K. (2019). Robust Sourcing from Suppliers under Ambiguously Correlated Major Disruption Risks. Production and Operations Management, 28(2), 441-456.

Appendix 1. Journals

Annals of Operations Research
Computers and Industrial Engineering
Decision Sciences
European Journal of Operational Research
Industrial Management and Data Systems
International Journal of Production Economics
International Journal of Production Research
Journal of Purchasing and Supply Management
Management Science
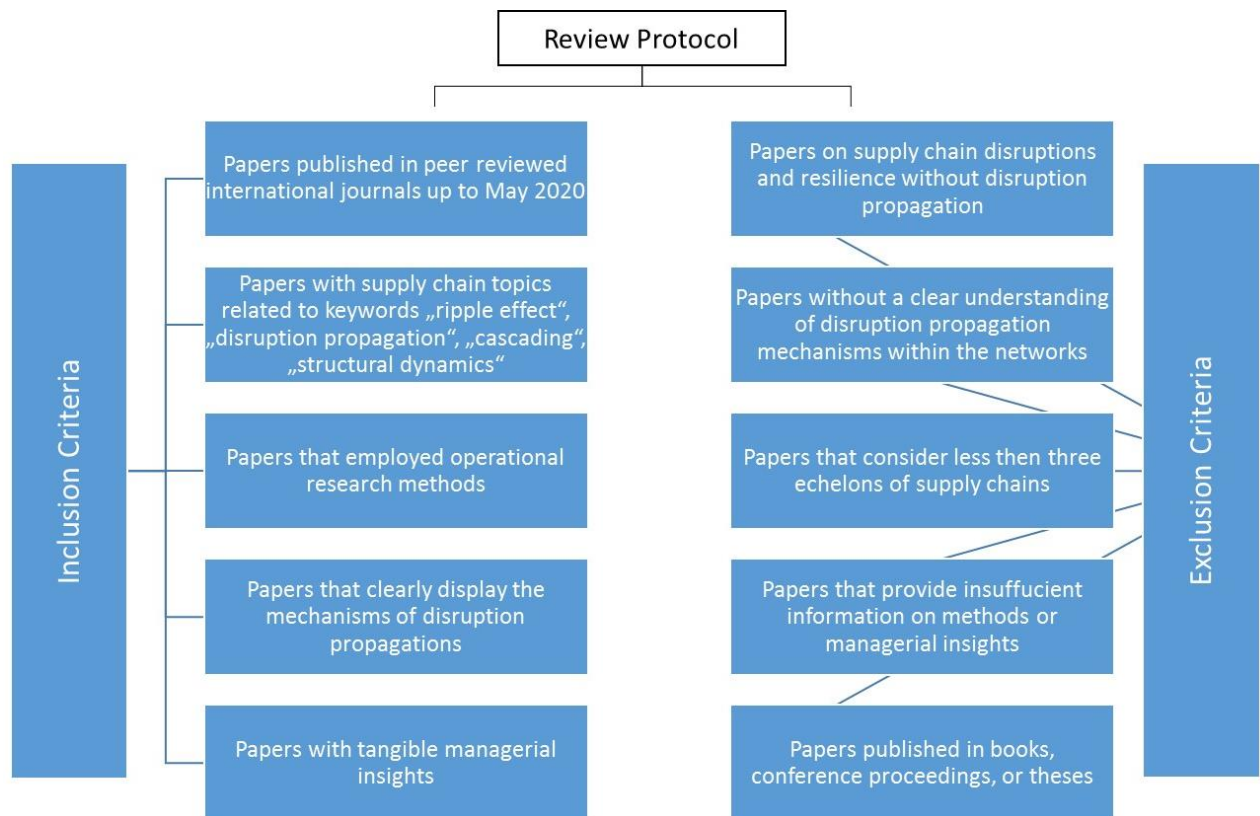*Manufacturing & Service Operations Management*
Omega
Physica A
Production and Operations Management
Supply Chain Management: An International Journal
Transportation Research Part E: Logistics and Transportation Review

Fig. 1. Literature selection criteria

Review Protocol

Inclusion Criteria

- Papers published in peer reviewed international journals up to May 2020
- Papers with supply chain topics related to keywords „ripple effect", „disruption propagation", „cascading", „structural dynamics"
- Papers that employed operational research methods
- Papers that clearly display the mechanisms of disruption propagations
- Papers with tangible managerial insights

Exclusion Criteria

- Papers on supply chain disruptions and resilience without disruption propagation
- Papers without a clear understanding of disruption propagation mechanisms within the networks
- Papers that consider less then three echelons of supply chains
- Papers that provide insuffucient information on methods or managerial insights
- Papers published in books, conference proceedings, or theses

Table 1. Theories used in the studies on the ripple effect and structural dynamics

Theory	Number of studies	Study
Agent-Based Simulation	1	Mizgier et al. (2012)
Bayesian Networks	6	Cao et al. (2019), Garvey et al. (2015), Garvey and Carnovale (2020), Hosseini and Ivanov (2019), Hosseini et al. (2019), Ojha et al. (2018)
Complexity theory	5	Basole and Bellamy (2014), Deng et al. (2019), Lei et al. (2020), Levner and Ptuskin (2018), Zeng and Xiao (2014)
Discrete-Event Simulation	4	Dolgui et al. (2020), Ivanov (2017, 2019, 2020)
Entropy	2	Levner and Ptuskin (2018), Zeng and Xiao (2014)
Graph theory	5	Basole and Bellamy (2014), Li et al. (2019), Li and Zobel (2020), Sinha et al. (2019), Sokolov et al. (2016)
Linear / Mixed-Integer Programming	6	Liberatore et al. (2012), Ivanov et al. (2013, 2014, 2015, 2016), Pavlov et al. (2019)
Markov Chains	1	Hosseini et al. (2019)
Monte-Carlo Simulation	1	Pariazar et al. (2017)
Optimal Control	5	Ivanov et al. (2010, 2013, 2014, 2015, 2016)
Petri Nets	1	Blackhurst et al. (2018)
Reliability Theory / Statistical Analysis	4	Hand and Shin (2016), Osadchiy et al. (2016), Pavlov et al. (2020), Tang et al. (2016)
Robust Optimization	3	Lu et al. (2015), Özçelik et al. (2020), Zhao and Freeman (2019)
Stochastic Optimization	2	Goldbeck et al. (2020), Pariazar et al. (2017)
Systems Dynamics	2	Bueno-Solano and.Cedillo-Campos (2014), Ghadge et al. (2013),

Table 2. Operational Research studies on the disruption propagations in the SCs

Authors and publication year	Title	Journal	Central focus	Method(s)	Outcomes & Managerial Insight(s)	Analysis level
Basole, R.C. and Bellamy, M.A. (2014)	Supply Network Structure, Visibility, and Risk Diffusion: A Computational Approach	Decision Sciences	Network proneness to disruption propagation	Graph theory; Complexity theory	Significant association between network structure and risk propagation; Small-world supply network topologies consistently outperform supply networks with scale-free characteristics	N
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	Visualization and mapping out of disruption propagation	Petri net and Triangularization Clustering Algorithm	Understand potential weaknesses in the SC design taking into account the structure, connectivity, and dependence within the SC	N
Bueno-Solano, A., Cedillo-Campos, M.G. (2014).	Dynamic impact on global supply chains performance of disruptions propagation produced by terrorist acts	Transportation Research Part E: Logistics and Transportation Review	Understanding disruption propagation propagate through the SC to ensure security and efficient movement of goods	System Dynamics simulation	Measures for disruption propagation can drastically increase the inventory levels in the SC	P
Cao, S., Bryceson, K., Hine, D. (2019).	An Ontology-based Bayesian network modelling for supply chain risk propagation	Industrial Management and Data Systems	To quantitatively assess the impact of dynamic risk propagation in fresh product SCs	Ontology-based Bayesian network	Supply discontinuity, product inconsistency and/or delivery delay originating from the ripple effect	N
Deng, X., Yang, X., Zhang, Y., Li, Y., Lu, Z. (2019).	Risk propagation mechanisms and risk management strategies for a sustainable perishable products supply chain.	Computers and Industrial Engineering	Identify dimensions of risk propagation SCs with perishable products	Tropos Goal-Risk framework	Three-dimension model to control the ripple effect (paths of risk propagation, dependencies between nodes, modes of risk propagation); sustainability issues connected to the ripple effects	N
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	To identify relations between the bullwhip effect and ripple effects	Discrete-event simulation	Ripple effect can be a bullwhip-effect driver, while the latter can be launched by a severe disruption even in the downstream direction; Backlog accumulation over the disruption time is the major influencer of the ripple effect on SC performance;	C

					SC visibility and information coordination is the key capability to cope with the ripple effect.	
Garvey, M.D., Carnovale, S. (2020)	The Rippled Newsvendor: A New Inventory Framework for Modelling Supply Chain Risk Severity In The Presence of Risk Propagation	International Journal of Production Economics	Inventory control policies with ripple effect considerations	Bayesian Network simulation	Reliability control of inventory policies; Managers should focus more of their attention on control or mitigation of exogenous events that directly impact their own firm, and spend less of an effort and resources on mitigating the propagation of exogenous risk from a supplier to an exogenous risk of the firm itself.	P
Garvey, M.D., Carnovale, S., Yeniyurt, S.	An analytical framework for supply network risk propagation: A Bayesian network approach	European Journal of Operational Research	Inter-dependencies among different risks, as well as the idiosyncrasies of SC structures	Bayesian Network simulation	Measuring disruption propagation in the SC to analyse network proneness to the ripple effect	N
Ghadge, A., Dani, S., Chester, M., & Kalawsky, R. (2013).	A systems thinking approach for modelling supply chain risk propagation	Supply Chain Management: An International Journal	Prediction of potential failure points in an SC and overall impact of the failure risks on performance	System Dynamics simulation	Prediction of potential failure points in the SC along with the overall impact of the ripple effect on the performance	P
Goldbeck, N., Angeloudis, P., Ochieng, W. (2020)	Optimal supply chain resilience with consideration of failure propagation and repair logistics	Transportation Research Part E: Logistics and Transportation Review	Resilient SC designs with considerations of the trade-offs between redundancy costs and disruption-resistance	Scenario tree generation method for risk propagation modelling; Multi-stage stochastic programming model	Joint optimisation of SC capacities and recovery capabilities for new and existing SCs; Trade-off between investments in increased recovery capability and redundant capacity provision; Decision-making support on safety stock management, reconfiguration of production and inventory plans after disruptions, and recovery scheduling	P
Han, J., Shin, K.S. (2016)	Evaluation mechanism for structural robustness of supply chain considering disruption propagation	International Journal of Production Research	Structural robustness evaluation	Reliability theory / Probabilistic analysis	To verify whether the SC design is robust to disruption propagation or not	N

Hosseini S., Ivanov D. (2019).	Resilience Assessment of Supply Networks with Disruption Propagation Considerations: A Bayesian Network Approach	Annals of Operations Research	Measuring of the ripple effect with consideration of both disruption and recovery stages	Bayesian Network simulation	To identify the resilience level of their most important suppliers; To identify the disruption profiles in the supply base and associated SC performance degradation due to the ripple effect.	N
Hosseini S., Ivanov D., Dolgui A. (2019).	Ripple effect modeling of supplier disruption: Integrated Markov Chain and Dynamic Bayesian Network Approach	International Journal of Production Research	Measuring of the ripple effect with consideration of state changes within individual SC nodes	Discrete-Time Markov Chain (DTMC) and a Dynamic Bayesian Network (DBN)	A metric that quantifies the ripple effect of supplier disruption on manufacturers in terms of total expected utility and service level; Uncovering latent high-risk paths in the SC and prioritising contingency and recovery policies	N
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	Production-ordering behaviour in an FMCG SC with disruption risks in recovery and post-disruption periods	Discrete-event simulation	Non-coordinated ordering and production policies during the disruption period may result in backlog and delayed orders, the accumulation of which causes post-disruption SC instability, resulting in further delivery delays and non-recovery of SC performance; Specific policies must be developed for the transition from the recovery to the disruption-free operations mode to avoid "disruption tails"	C
Ivanov D. (2020)	Predicting the impact of epidemic outbreaks on the global supply chains: A simulation-based analysis on the example of coronavirus (COVID-19 / SARS-CoV-2) case	Transportation Research Part E: Logistics and Transportation Review	Predicting the impact of epidemic outbreaks on the global SCs	Discrete-event simulation	Timing of the closing and opening of the facilities at different echelons might become a major factor that determines the epidemic outbreak impact on the SC performance Lead-time, speed of epidemic propagation, and the upstream and downstream disruption durations in the SC are other important factors; Results can be used to predict the operative and long-term impacts of epidemic outbreaks on the SCs and develop pandemic SC plans; to identify the successful and wrong	C

					elements of risk mitigation/preparedness and recovery policies in case of epidemic outbreaks	
Ivanov D., Sokolov B., Pavlov, A. (2013)	Dual problem formulation and its application to optimal re-design of an integrated production-distribution network with structure dynamics and ripple effect considerations	International Journal of Production Research	Identify a SC design structure that would satisfy some performance criteria under different disruptions	Optimization: linear Programming	Building robust distribution plans and interconnecting decisions on distribution network design, planning, and sourcing.	P
Ivanov, D. (2017)	Simulation-based the ripple effect modelling in the supply chain	International Journal of Production Research	Performance impact of disruption propagation in the SC	Discrete-event simulation	Advantages and costs of backup SC designs for mitigating the ripple effect	C
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	SC multi-structural design and dynamic control of macro-states	Control theory	SC designs are not restricted to the network of firms; rather they are multi-structural systems spanning organizational, informational, financial, technological, process-functional and product structures	N
Ivanov, D., Sokolov, B., & Dolgui, A. (2014b)	The ripple effect in supply chains: Trade-off 'efficiency-flexibility-resilience' in disruption management	International Journal of Production Research	Conceptualization of the ripple effect concept in SCs; Dynamic view on SC ripple effect	Control theory	Disruption propagation represents a specific type of SC risks, i.e., the ripple effect	N
Ivanov, D., Sokolov, B., & Pavlov, A. (2014a)	Optimal distribution (re)planning in a centralized multi-stage network under conditions of the ripple effect and structure dynamics	European Journal of Operational Research	Reconfiguration of material flows in an SC subject to changes in the network structures over many periods	Optimization: linear programming and optimal control	Considering different execution scenarios and developing suggestions on replanning in the case of disruption propagation; scenario-based risk identification strategy and operational distribution planning	P
Ivanov, D., Sokolov, B., Hartl, R., Dolgui, A., Pavlov, A., Solovyeva, I. (2015)	Integration of aggregate distribution and dynamic transportation planning in a supply chain with capacity disruptions and ripple effect considerations	International Journal of Production Research	Distribution and transportation capacity disruptions and the ripple effect	Optimization: linear programming and optimal control	Dynamic, time-dependent issues of the ripple effect	P
Ivanov, D., Sokolov, B., Pavlov, A., Dolgui, A., & Pavlov, D. (2016)	Disruption-driven supply chain (re)-planning and performance im-	Transportation Research Part E: Logistics and	Impact of disruption durations on the ripple effect and SC performance with	Optimization: linear programming and optimal control	To analyze proactive SC structures, compute recovery policies and to redirect material flows to mitigate the ripple effect;	P

	pact assessment with consideration of pro-active and recovery policies	Transportation Review	consideration of recovery costs		Method to compare SC design resistance to the ripple effect; Suggesting rules to recover and re-allocate resources and flows after a disruption	
Lei, Z., Lim, MK., Cui L. & Y. Wang (2020).	Modelling of risk transmission and control strategy in the transnational supply chain.	International Journal of Production Research.	Mechanisms of risk transmission in the global SCs	Susceptible-infectious-susceptible (SIS) model; complexity theory	Global supplier diversification and risk control are crucial management activities to mitigate the ripple effect	N
Levner E., Ptuskin A. (2018)	Entropy-based model for the ripple effect: managing environmental risks in supply chains	International Journal of Production Research	Impact of environmental risks on the ripple effect	Complexity theory; entropy analysis	Assessing the economic loss caused by ripple effect due to environmental risks	N
Li, Y., Zobel, C. W. (2020).	Exploring Supply Chain Network Resilience in the Presence of the Ripple Effect	International Journal of Production Economics	Impact of the ripple effect on SC resilience	Graph theory; simulation	Network type has more influence on the resistance to the ripple effect in a short-term perspective; In long-term perspective, it is more advantageous to enhance the node risk capacity as adjust the structure; Increasing robustness may lead to longer recovery time	N
Li, Y., Zobel, C. W., Seref, O., and Chatfield, D. C. (2019)	Network Characteristics and Supply Chain Resilience under Conditions of Risk Propagation	International Journal of Production Economics	Impact of network characteristics on SC resilience with disruption propagation considerations	Graph theory	Metrics to analyse impact of the ripple effect on SC resilience; The recovery time is primarily determined by the disruption process, and much less so by the network structure	N
Liberatore F, Scaparra M.P., Daskin M.S. (2012).	Hedging against disruptions with ripple effects in location analysis	Omega	How to fortify SC facilities to hedge against the ripple effect	Optimization: mixed-integer programming	Identification of facilities to be fortified to mitigate the ripple effect	P
Lu, M., Ran, L., Shen, Z.-J.M. (2015)	Reliable facility location design under uncertain correlated disruptions	Manufacturing & Service Operations Management	Worst-case analysis of reliable facility location problem with consideration of correlated disruptions	Robust optimization	Reliable SC design with costs minimization for some given disruption probabilities of correlated events	P
Mizgier, KJ, SM Wagner, JA Holyst (2012)	Modeling defaults of companies in multi-stage supply chain networks	International Journal of Production Economics	Modeling defaults of companies caused by structural dynamics	Agent-based simulation	If a company is not able to quickly adapt to the changing environment, it might be exposed to the risk of collective defaults of suppliers, which	N

					can give rise to disruptions and delays in production.	
Ojha, R., Ghadge, A., Tiwari M.K. & U. S. Bititci (2018)	Bayesian network modelling for supply chain risk propagation	International Journal of Production Research	Analysis of SC exposure to the ripple effect risk	Bayesian Network simulation	Ripple effect quantification by fragility, service level, inventory cost and lost sales	N
Osadchiy, N., Gaur, V., Seshadri, S. (2016)	Systematic risk in supply chain networks	Management Science	Mapping supply networks of industries and firms to investigate how the SC structure mediates the effect of economy on industry or firm sales.	Statistical analysis	To identify mechanisms that can affect the correlation between sales levels and the SC states; Effects of risk propagation into production decisions, aggregation of orders from multiple customers in an SC and aggregation of orders over time.	N
Özçelik, G., Ö. F. Yılmaz & F. B. Yeni (2020)	Robust optimisation for ripple effect on reverse supply chain: an industrial case study	International Journal of Production Research	Ripple effect in the reverse SC	Robust optimization	Method to proactively increase SC design robustness against the ripple effect with consideration of reverse network	P
Pariazar, M., Root, S., Sir, M.Y. (2017).	Supply chain design considering correlated failures and inspection in pharmaceutical and food supply chains	Computers and Industrial Engineering	Impact of correlated disruptions on the SC design	Stochastic programming; Monte-Carlo simulation	Correlated supplier failures increase total cost and influence SC design	P
Pavlov A., Ivanov D., Pavlov D., Slinko A. (2019)	Optimization of network redundancy and contingency planning in sustainable and resilient supply chain resource management under conditions of structural dynamics	Annals of Operations Research	Search for an optimal SC design and the intensities of the processing policies at the nodes and arcs subject to multi-period changes in network structures and budget restrictions	Optimization: linear programming	To identify the balanced levels of capacity utilization and production rates at different firms in the SC to achieve maximum performance.	P
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	Identification of disruption scenarios of different severity and the resulting ripple effects	Reliability theory	A methodology to identify most sever disruption scenarios, the respective ripple effects and optimal recovery paths	N
Sinha, P., Kumar, S., Prakash S. (2019)	Measuring and Mitigating the Effects of Cost Disturbance Propagation in Multi-Echelon Apparel Supply Chains	European Journal of Operational Research	Impact of demand variation propagation on the SC performance	Graph theory	SC reconfiguration strategies to reduce the negative impact of disturbance propagation	P
Sokolov, B., Ivanov, D., Dolgui A., Pavlov A. (2016).	Structural quantification of the ripple effect in the supply chain	International Journal of Production Research	Analysis of different performance indicators under	Graph theory, MCDM	Interrelations between network robustness, centralization and flexibility	N

			uncertainty for SCs with the ripple effects			
Tang, L., K. Jing, J. He, H.E. Stanley (2016)	Complex interdependent supply chain networks: Cascading failure and robustness	Physica A	Robustness of cyber-physical SC with disruption propagation considerations in material and information flows	Reliability theory	Helps to identify the critical nodes the removing of which would lead to network discontinuity or even collapses	N
Zeng, Y., & Xiao, R. (2014).	Modelling of cluster supply network with cascading failure spread and its vulnerability analysis	International Journal of Production Research	Analysis and mitigation of SC vulnerability in the presence of the disruption propagation	Complexity theory; entropy analysis	Analyse and predict the dynamic SC behaviours cause by vulnerabilities during the process of failure spreading	N
Zhao M., Freeman, N.K. (2019)	Robust Sourcing from Suppliers under Ambiguously Correlated Major Disruption Risks	Production and Operations Management	Sourcing policies under conditions of ambiguously correlated disruptions	Distributionally robust model	Profit maximization for scenarios with the worst-case disruption distribution.	P

Table 3. Outcomes and managerial insights from OR contributions to the ripple effect and structural dynamics

Level of Analysis	OR methods	Outcomes	Managerial insights
Network Level	Graph theory Complexity theory Entropy Petri Nets Bayesian Networks Markov Chains Reliability Theory / Statistical Analysis	• Associations between network structures and risk propagation; • Analysis of critical network elements leading to supply chain discontinuities and collapses through the cascading failure effects; • Modelling of interdependencies in SCs; • State dynamics within SC nodes; • Assessment of SC robustness and resilience to disruptions with the ripple effect considerations	• Identification of disruption propagation scenarios of different severity • Stress-testing of SC designs • Proneness of specific SC designs to disruption risk propagation • Identification of critical suppliers and facilities for maintaining SC operations • Selection and proactive enhancements of SC designs to sustain certain levels of disruption propagations and structural dynamics • Adaptation of SC designs according to the environmental changes
Process Level	Stochastic Optimization Robust Optimization Linear / Mixed-Integer Programming	• Optimal reconfigurations of material flows according to disruption propagation scenarios • Impacts of the ripple effect and structural dynamics on service level and costs • Optimal re-allocation of supply and demand under conditions of disruption propagation and structural dynamics	• Stress-testing of SC production-distribution plans within differently disrupted network designs • Analysis of contingency / preparedness plans • Recovery plan selection
Control Level	Optimal Control Systems Dynamics Agent-Based Simulation Discrete-Event Simulation	• Impacts of the disruption propagations on service level, inventory levels, and costs • Time-dependent effect of disruption propagation on SC behaviors and performance in dynamics • Individual behaviors of firms in SCs	• Building resilient SCs for new, after-pandemic business models • Analysis of the disruption propagation in dynamics with considerations of production and inventory control policies • Simulation of operations policies during the disruption, in transition to recovery, and in the post-recovery periods

Table 4. Suggestions for future research and applications in the pandemic settings

Pandemic stages	Suggestions for future research and applications of OR methods in the pandemic settings	
	Managerial applications	*Future research directions*
Anticipation and early detection	• Identify critical scenarios of disruption propagation according to an epidemic outbreak dynamics • Forecast the impact of possible propagating disruptions on SC performance • Predict the time periods during which the SCs can sustain the disruption propagations and survive despite the discontinuities • Identify critical suppliers and facilities for maintaining SC operations • Implement "Design-for-Resilience" network structures • Select and fortify SC designs to sustain epidemic outbreaks	• Develop theories and models for disruption propagation analysis in supply networks with specific consideration of pandemics • Visualize the ripple effect and structural dynamics • Multi-categorical analysis spanning dimensions of resilience and sustainability • Examine new analysis categories such as network viability • Investigate the data analytics and digital technologies to early detect the disruption propagations following epidemic outbreaks
Containment	• Stress-testing of SC configurations and production-distribution plans for some scenarios of structural dynamics in anticipation of facility/market closure due to quarantines • Optimise contingency / preparedness plans for deployment under different scenarios of epidemic propagation	• Examine new understanding, theories, and novel approaches concerning SC preparedness and disruption mitigation during the beginning epidemic outbreaks • Articulate antecedents, drivers, and economic and social performance implications of simultaneous disruption and epidemic propagations

Control and mitigation	• Analyse the impacts of disruption propagation in dynamics with adaptations of ordering, production and inventory control policies
	• Simulate and articulate operations policies amid the pandemic
	• Explore re-allocations of supply and demand during the pandemic given simultaneous disruptions in upstream and markets
	• Re-design the SCs for production switches to unusual products (e.g., mask production at car manufacturers)
	• Propose recovery plan selection with analysis of timing and scaling of facility/market closures and openings in different geographical regions
		• Develop and test new theories, models, and resilience mechanisms for control and mitigation of disruption propagation in SCs with specific consideration of pandemic features, such as:
		  - long-term disruption existence and its unpredictable scaling;
		  - simultaneous disruption propagation and epidemic outbreak propagation;
		  - simultaneous severe disruptions in supply, demand, and logistics infrastructure
		• Develop and examine digital SC twins to map the network elements and adapt the SC according to disruption propagations and structural dynamics
		• Explore the role of timing and scaling the production and logistics ramp-ups after the quarantines and lock-down eliminations

Elimination	• Incorporate after-pandemic environments in the re-designing of the SCs • Examine the existing and potential SC configurations under post-pandemic conditions in the supply base and the markets • Analyse the "disruption tails" and long-term stabilization of production-inventory systems	• Find optimal scaling and timing of production and logistics ramp-ups during the "exit" after the lock-downs • Examine SC re-design methods for sever structural changes in supply and demand after a pandemic (e.g., supplier bankruptcies and demand drops/shifts) • Explore the concept of SC viability as a long-term maintaining of survivability

		under different and ever changing environmental conditions