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
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.


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):

\[
\text{supply AND chain AND disruption) AND (ripple) OR (cascade) OR (cascading) OR (propagation) OR (correlated AND disruption) OR (structural AND dynamics) OR (transmission)}
\]

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.

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)

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.

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.

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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 area 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 severe 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


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

- **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 than three echelons of supply chains
  - Papers that provide insufficient 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

<table>
<thead>
<tr>
<th>Theory</th>
<th>Number of studies</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent-Based Simulation</td>
<td>1</td>
<td>Mizgier et al. (2012)</td>
</tr>
<tr>
<td>Complexity theory</td>
<td>5</td>
<td>Basole and Bellamy (2014), Deng et al. (2019), Lei et al. (2020), Levner and Ptuskin (2018), Zeng and Xiao (2014)</td>
</tr>
<tr>
<td>Entropy</td>
<td>2</td>
<td>Levner and Ptuskin (2018), Zeng and Xiao (2014)</td>
</tr>
<tr>
<td>Graph theory</td>
<td>5</td>
<td>Basole and Bellamy (2014), Li et al. (2019), Li and Zobel (2020), Sinha et al. (2019), Sokolov et al. (2016)</td>
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<tr>
<td>Markov Chains</td>
<td>1</td>
<td>Hosseini et al. (2019)</td>
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<td>Monte-Carlo Simulation</td>
<td>1</td>
<td>Pariazar et al. (2017)</td>
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<td>Petri Nets</td>
<td>1</td>
<td>Blackhurst et al. (2018)</td>
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<tr>
<td>Robust Optimization</td>
<td>3</td>
<td>Lu et al. (2015), Özçelik et al. (2020), Zhao and Freeman (2019)</td>
</tr>
<tr>
<td>Stochastic Optimization</td>
<td>2</td>
<td>Goldbeck et al. (2020), Pariazar et al. (2017)</td>
</tr>
<tr>
<td>Authors and publication year</td>
<td>Title</td>
<td>Journal</td>
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<tr>
<td>Basole, R.C. and Bellamy, M.A. (2014)</td>
<td>Supply Network Structure, Visibility, and Risk Diffusion: A Computational Approach</td>
<td>Decision Sciences</td>
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<tr>
<td>Bueno-Solano, A., Cedillo-Campos, M.G. (2014).</td>
<td>Dynamic impact on global supply chain performance of disruptions propagation produced by terrorist acts</td>
<td>Transportation Research Part E: Logistics and Transportation Review</td>
</tr>
<tr>
<td>Dolgui A., Ivanov D., Rozhkov M. (2020).</td>
<td>Does the ripple effect influence the bullwhip effect? An integrated analysis of structural and operational dynamics in the supply chain</td>
<td>International Journal of Production Research</td>
</tr>
<tr>
<td>Garvey, M.D., Carnovale, S. (2020)</td>
<td>The Rippled Newsvendor: A New Inventory Framework for Modeling Supply Chain Risk Severity In The Presence of Risk Propagation</td>
<td>International Journal of Production Economics</td>
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</table>
Table 3. Outcomes and managerial insights from OR contributions to the ripple effect and structural dynamics

<table>
<thead>
<tr>
<th>Level of Analysis</th>
<th>OR methods</th>
<th>Outcomes</th>
<th>Managerial insights</th>
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<tbody>
<tr>
<td>Network Level</td>
<td>Graph theory</td>
<td>• 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</td>
<td>• 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</td>
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<tr>
<td></td>
<td>Complexity theory</td>
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<td>Entropy</td>
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<td>Petri Nets</td>
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<td>Bayesian Networks</td>
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<td>Markov Chains</td>
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<td></td>
<td>Reliability Theory / Statistical Analysis</td>
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<td>Process Level</td>
<td>Stochastic Optimization</td>
<td>• 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</td>
<td>• Stress-testing of SC production-distribution plans within differently disrupted network designs • Analysis of contingency / preparedness plans • Recovery plan selection</td>
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<tr>
<td></td>
<td>Robust Optimization</td>
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<td>Linear / Mixed-Integer Programming</td>
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<td>Control Level</td>
<td>Optimal Control</td>
<td>• 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</td>
<td>• 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</td>
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<td></td>
<td>Systems Dynamics</td>
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<td>Agent-Based Simulation</td>
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<td>Discrete-Event Simulation</td>
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### Table 4. Suggestions for future research and applications in the pandemic settings

<table>
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<tr>
<th>Pandemic stages</th>
<th>Managerial applications</th>
<th>Future research directions</th>
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</table>
| **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 severe 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 |