Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: a research note

Dmitry Ivanov*

Supply Chain and Operations Management,
Department of Business Administration,
Berlin School of Economics and Law,
10825, Berlin, Germany
Email: divanov@hwr-berlin.de
*Corresponding author

Ajay Das

Narendra Paul Loomba Department of Management,
Zicklin School of Business,
Baruch College,
CUNY-Baruch,
CUNY,
One Bernard Baruch Way, 10010,
New York, NY, USA
Email: ajay.das@baruch.cuny.edu

Abstract: Firms have learned how to strengthen the resilience of their global supply chains (SC) to confront disruptions triggered by severe disasters. However, a new instigator of SC disruption, quite unlike any seen in recent times, has now emerged – the COVID-19/SARS-CoV-2 virus. We model the ripple effect of an epidemic outbreak in global SCs considering the velocity of pandemic propagation, the duration of production, distribution and market disruption, and a demand decline. We analyse pandemic supply risk mitigation measures and potential recovery paths. Implications for future research and global SC (re)-designs are also discussed.

Keywords: supply chain; risk management; resilience; epidemic outbreak; Coronavirus; COVID-19; SARS-CoV-2; pandemic plan; simulation; digital twin; ripple effect.

Reference to this paper should be made as follows: Ivanov, D. and Das, A. (2020) 'Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: a research note', *Int. J. Integrated Supply Management*, Vol. 13, No. 1, pp.90-102.

Biographical notes: Dmitry Ivanov is a Professor of Supply Chain and Operations Management at Berlin School of Economics and Law (HWR Berlin). He gained his Dr., Dr. Sc, and Dr. Habil. degrees and won several research excellence awards. His publication list includes around 330 publications, including 85 papers in international academic journals (e.g., *EJOR*, *IISE Transactions*, *IJPR*, *IJPE*, *Omega*, and *TRE*) and a leading textbook *Global Supply Chain and Operations Management*. His main research interests and results are spread over the ripple effect control in supply chains, development of supply chain structural dynamics control methods, and digital supply chain twins.

Ajay Das earned his PhD in Supply Chain and Operations Management at Michigan State University. His current research interests span innovation, risk, technology, and worker aging effects. His research has appeared in the *Journal of Operations Management*, *Decision Sciences*, *IJPR*, *IJOPM*, *JSCM*, and *IJPE*, amongst others. His research is preceded and influenced by several years in industry operations. His pedagogical perspective on synthesising concept and practice finds voice in his textbook *An Introduction to Operations Management: The Joy of Operations!* (© 2016 – Routledge). He encourages and invites international collaboration in research (and pedagogy) of mutual interest.

1 Introduction

Low-frequency-high-impact (LFHI) events pose considerable risk to supply chains (SCs) (Ivanov et al., 2017; Kinra et al., 2019; Hosseini et al., 2019; Ivanov et al., 2019b). The effects of such events cascade through a SC in what is termed a 'ripple effect' (Ivanov et al., 2014). We consider epidemic outbreaks as a special category of a LFHI SC risk.

Businesses have taken steps to strengthen the resilience of their global SCs to risks posed by natural or industrial LFHI events – for, e.g., Hurricane Katrina in 2005, the earthquake and tsunami in Japan in 2011, an explosion at the BASF plant in 2016. SC resilience has been fortified by investments in risk mitigation inventories, subcontracting capacities, backup supply and transportation infrastructures, and data-driven, real-time monitoring and visibility systems (Tang, 2006; Tomlin, 2006; Craighead et al., 2007; Ivanov, 2018b; Choi et al., 2019; Xu et al., 2020; Dolgui et al., 2020). For example, following Schmidt and Simchi-Levi (2013), Nissan has developed a SC resilience program that encompasses SC monitoring and visibility, geographic supply diversification, and flexible re-allocation of demand and supply in the case of disruptions.

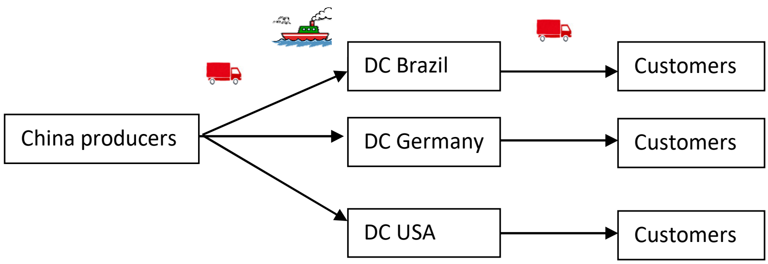
A pandemic generated SC disruption shares a LFHI profile with other SC risks. It also manifests the well-recognised 'ripple effect' seen in LFHI event impacts (Dolgui et al., 2018; Ivanov et al., 2019d). Reports of COVID virus caused downstream interruption and closure of production and distribution activities in many SCs abound. As widely reported, Apple's assembler, Foxconn, is working below capacity. Apple's suppliers in Malaysia, South Korea and Europe have too been affected by government lockdowns and a paucity of parts supplies from their own sub-suppliers. A recent survey by ISM of about 600 US companies revealed that suppliers are operating at an average 50% capacity leading to longer final product lead times for 57% of those surveyed and a negative revenue impact ranging between 5.6%–15% (ISM, 2020). Shorter lead times and JIT have accelerated the ripple effect of sup-ply base disruption through SCs.

However, a pandemic has quite unique implications for SCs. In contrast to geographically centred, singular occurrence natural/industrial disasters, a pandemic is not limited to a particular region or confined to a particular time period. Different components of a SC are affected sequentially or concurrently – manufacturing, distribution centres (DCs), logistics, and markets can become paralysed within overlapping time windows. This research note investigates and highlights some of the unique consequences of a pandemic on a SC.

2 Simulation study setup and analysis

In this section, we analyse the results of a simulation that examines the impact of a pandemic on a global SC that has China located upstream facilities (technical details available from corresponding author) (see Figure 1).

Figure 1 SC design for simulations (see online version for colours)



Our SC network design comprises of upstream manufacturers in China, using multi-modal transportation to ship products to DCs in Brazil, Germany, and the USA, The average lead transportation time from China to a DC is 30 days with some variations. The lead times from DCs to customers are about 3–7 days. DCs truck the goods to their customers. We modelled three distinctive, but sequential, scenarios:

- Scenario I: Epidemic originates in, and is limited to China producer regions.
- Scenario II: Epidemic propagates to DCs.
- Scenario III: Epidemic propagates to customers – demand disrupts by 50%.

Scenarios could co-exist, or exist independently at different points in time. However, the market disruptions happen in the same time frame as the downstream DC disruptions caused by quarantine measures.

Propagation and ripple effect were considered in three aspects: the speed of epidemic propagation, the resultant duration of the disruption at DC node, and the duration of the reduced (50% drop) demand period. We examined different disruption durations and scales of epidemic propagation. In total we investigated 39 simulation setups which resulted as follows.

Scenario I considers three different epidemic durations and the resulting production stops at the producers in China of 45 days, 60 days or 90 days. These numbers are based on actual or forecasted quarantine times in China in January–March 2020.

Scenario II extends the scenario I by adding epidemic propagation to USA, Germany and Brazil which results in 12 different simulation setups. First, we looked at two different setups with a fast and slow epidemic propagations of 30 and 60 days, respectively. These times are based on the actual numbers on the start of the quarantine measures outside China. For example, if an epidemic outbreak begins in China on 15 January, we setup epidemic outbreak downstream the SC with a delay of either 30 days (i.e., begin on 15 February) or 60 days (i.e., begin on 15 March). Second, we setup two different lengths of the disruption periods in the USA, Germany and Brazil of 45 or 90 days. These numbers are based on the actual or fore-casted durations of the quarantine measures (e.g., in Germany the quarantine measures were introduced on

16 March until 20 April; with a declared possibility of prolongation for another 45 days if the epidemic outbreak will not be dampened by 20 April). An example of such a combined setup is a disruption in China for 45 days (say from 15 January by 29 February), begin of an epidemic outbreak in Germany in 60 days after the epidemic outbreak in China (i.e., on 15 March), and the resulting disruption duration at the DC in Germany of 90 days (i.e., from 15 March by 15 June). In total, we have 12 different setups considering combinations of the upstream disruption duration, propagation speed of the epidemics downstream, and the downstream disruption duration. Finally, in Scenario III we extended the 12 setups from the Scenario II by adding demand disruption of 50% in the markets in USA, Germany, and Brazil of a short or long duration of 45 or 90 days, respectively. We assume that the market disruptions occur in the same time frame as the downstream DC disruptions. The rationale behind these setups are the observed trends for demand and capacity decreases during the quarantine times. This extension resulted in 24 new simulation setups. Table 1 presents selected, specimen simulation runs. A fuller simulation is available in Ivanov (2020b).

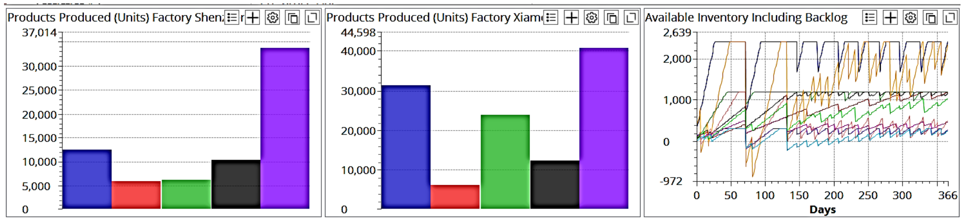
Table 1 Results of specimen simulation runs

No.	*Scenario*	*Upstream disruption duration*	*Delay in epidemic outbreak downstream the SC*	*Downstream disruption duration*	*Duration of market disruption (demand drops by 50%)*	*On-time delivery, %*	*Revenue, $*	*Profit, $*
	No disruption	0	0	0	0	89	108,100	28,568
1	*I*	45	0	0	0	84	108,028	19,005
2	*II*	45	60	45	0	75	102,130	11,969
3		45	60	90	0	64	88,072	–215
4		60	60	45	0	71	92,259	7,241
5	*III*	45	30	45	45	82	97,026	12,431
6		45	60	45	45	82	98,031	9,448
7		45	60	90	45	70	90,947	3,789
8		60	30	45	45	82	97,026	12,106
9		45	60	90	90	75	87,484	2,133
10		60	60	90	90	69	77,490	–268
11		90	60	90	90	69	77,490	–734

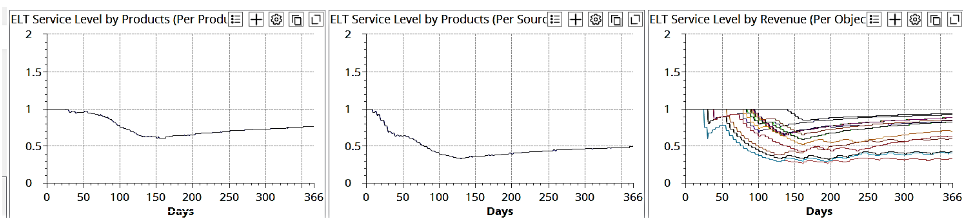
Expectedly, Scenario I, where the epidemic's impact is still confined to China, sees performance declines, stock outs, and price variability. In such conditions, the duration of the (yet limited) disruption affects SC performance (cf. line 1, Table 1). Interesting insights emerge in Scenario II. Now SC performance is seen to be a function of pandemic propagation velocity and the duration of pandemic induced downstream disruption

Consider Figures 2 and 3 illustration for lines 2 and 3 in Table 1 (see Figures 2 and 3).

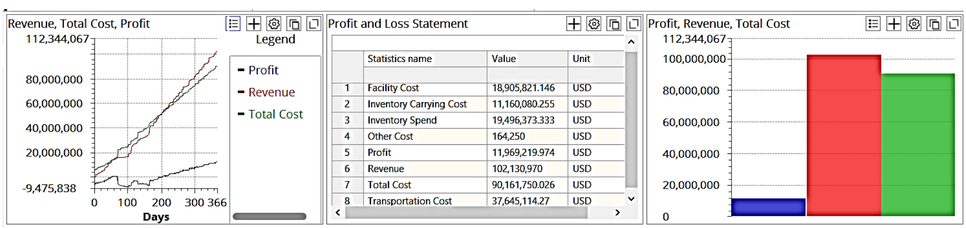
Figure 2 SC performance in Scenario II with 45 days of upstream disruption, 60 days delay in epidemic outbreak downstream, and 45 days downstream disruption (line 2 in Table 1), (a) production inventory dynamics (b) customer (ELT service level) performance (c) financial performance (d) lead-time performance (see online version for colours)



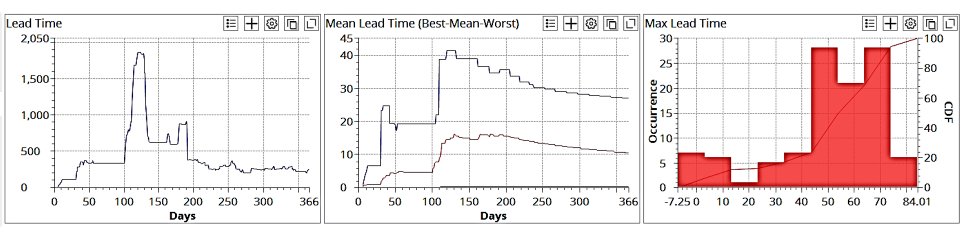
(a)



(b)



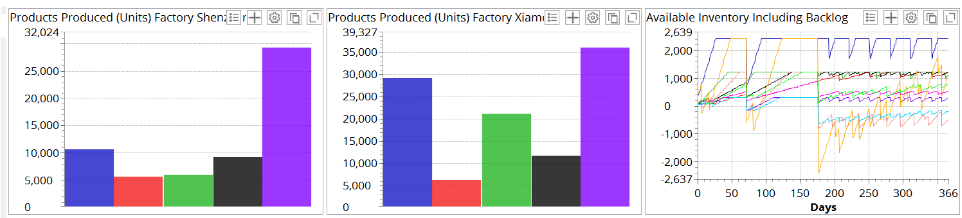
(c)



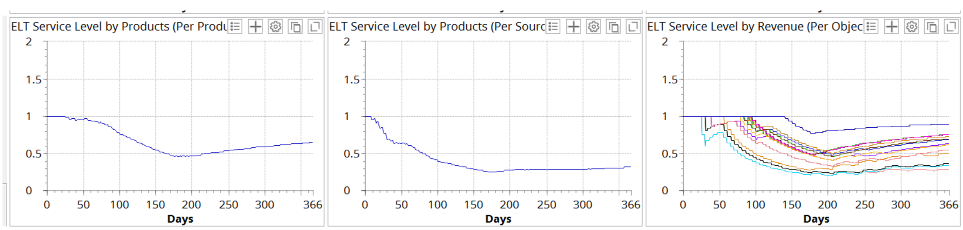
(d)

Figures 2 and 3 respectively contrast the difference in SC performance under the 60 and 90 days downstream disruption duration cases (other conditions identical) in Scenario II. Performance improves in terms of profit, service level, and lead times, when the timing of facility recovery at different echelons in the SC is synchronised. For example, in the case with 45 days disruption in China, 60 days delay in epidemic propagation, and 45 days of disruption downstream, we may have a situation when China production stops on 25 January, the DCs downstream close on 25 March, China production resumes on 10 March, and DC operations resume on 10 May. We can observe in Figure 2 that inventory dynamics minimise backlogs to a single backlog event, allowing a quick recovery. The production quantities for five different products are depicted in the bar chart of production inventory dynamics with different colours. Inventory dynamics stabilise quickly while on-time delivery (i.e., the ELT service level) improves. Performance thus appears to be a function of the timing of closure and opening of upstream production and downstream DC facilities. A complete shutdown of the SC is avoided, since there are material flows in the SC at every point in time.

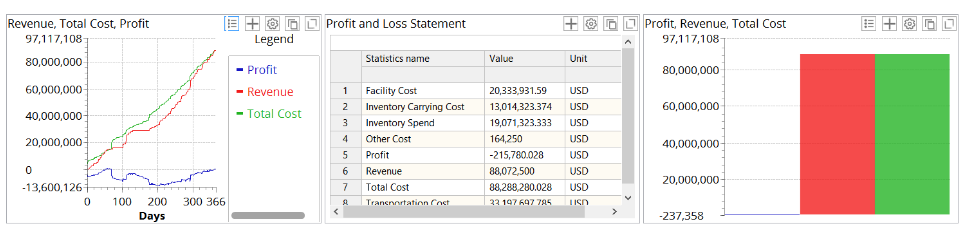
Figure 3 SC performance in Scenario II with 45 days of upstream disruption, 60 days delay in epidemic outbreak downstream, and 90 days downstream disruption (line 3 in Table 1), (a) production inventory dynamics (b) customer (ELT service level) performance (c) financial performance (d) lead-time performance (see online version for colours)



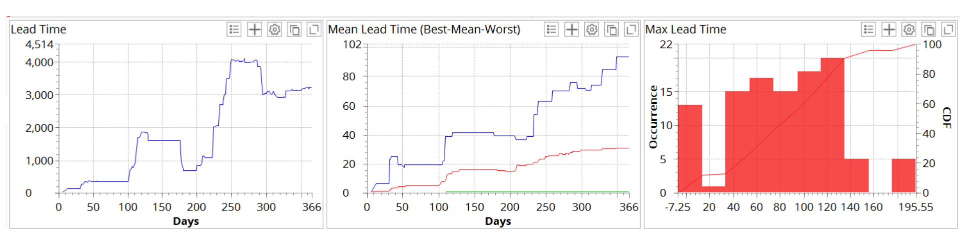
(a)



(b)



(c)



(d)

On the contrary, a longer downstream disruption (90 days instead of 45 days), keeping up-stream disruption duration and pandemic propagation speed unchanged, results in performance deterioration. Profits dip into negative territory while inventory dynamics remain un-stable for several months. Lead times increase and destabilise accompanied by a decline and non-recovery of ELT service level (cf. Figure 3).

Our simulation thus suggests that as epidemics propagate, SC performance depends on the timing (e.g., 30 or 60 days between the upstream and downstream epidemic outbreaks) and scale of disruption propagation (i.e., the ripple effect), as well as the sequence of facility closing and opening at different SC echelons. The disruption duration of upstream facilities does not impact as strongly on performance.

Scenario III introduces the added uncertainty of market disruption of varying durations in an attenuated demand situation (demand drops by 50%), against the general backdrop of variable upstream and downstream disruption times and variable pandemic velocity. Backorder and lost sales costs are not included in this preliminary examination. Interestingly, the combinatorial effects of negative events, happening concurrently, may actually improve SC performance. The best case in terms of SC performance is seen when facility recovery at different echelons in the SC is synchronised across time (see lines 5 and 8 in Table 1). The worst performance is seen in cases with extended DC facility and demand disruption durations, irrespective of the disruption period in the upstream China-based production (see lines 10 and 11 in Table 1).

3 Insights and future research areas

3.1 Potential remedies

We note that epidemic outbreaks have multiple, intersecting, interactive impacts on a SC. Traditional SC risk resilience practices of holding risk mitigation inventory for some weeks of a possible disruption or having subcontracting facilities, might need adaptations. Proactive measures such as inventory hoarding can help only at the beginning of an epidemic due to potential for very long disruption times. Similarly, backup suppliers and subcontracting facilities would be simultaneously or gradually impacted by regional, national or continental lock-downs and quarantines. As such, our sentiment is that the focus of SC resilience management while considering epidemic outbreaks should rather shift towards situational responses to real-time changes, rather than building proactive redundancies. For instance, our preliminary simulation of the impact of an epidemic on a SC suggests a SC performance collapse in certain conditions. As the simulation suggests, one way to avoid such SC wise paralysis is to time the closing and opening of the facilities at different SC echelons, inasmuch as possible.

At the same time, the importance of proactive management does not disappear. A difficult, but increasingly important proactive task is that of accurately mapping product SCs beyond the first or second supply tiers (Ivanov, 2017, 2018a, 2019; Ivanov and Rozhkov, 2017). Here, the focus would be shifted towards creating a *flexible redundancy* which would make the SC networks less sensitive to external uncertainties (Pavlov et al., 2019a, 2019b). A conceptual step in this direction is the low-certainty-need (LCN) SC framework (Ivanov and Dolgui, 2019). Rapid global crisis detection and response systems for capacity, inventory and freight, would be a part of such arrangements, as would related risk mitigation plans, and product designs that incorporate component switching options. Associated proactive plans may see an increase in the use of robotics and automated production and distribution systems – robots do not catch a virus, and do not have mortgages to pay when they are furloughed or laid off. Proactive plans, however, often are not eventually implemented for reasons of cost and inertia (once the crisis retreats).

3.2 Future research avenues on epidemic impact prediction and operating at the pandemic times

Literature on analysing the impacts of epidemic outbreaks on the commercial SCs is scarce. Opportunity exists to develop substantial contributions in this domain. The literature on humanitarian logistics, e.g., Lee et al. (2009), Koyuncu and Erol (2010), Dasaklis et al. (2012), Green (2012), Mamani et al. (2013), Altay and Pal (2014), Altay et al. (2018), Anparasan and Lejeune (2018), Dubey et al. (2019), Esra Büyüktahtakın et al. (2018) and Farahani et al. (2020) may provide useful pointers. Another path is to carefully observe behaviours and changes in selected SCs during COVID-19 times for developing empirically-grounded analytics studies. To wit, SCs of vital items in an epidemic such as medical equipment like ventilators and medical consumables such as masks, gloves, hand sanitizers and drugs.

Issues of research interest could include: operational scoping of the extended impact of an epidemic originating in a lead SC entity location, on both upstream and downstream constituents; estimating business impact; inflection points in the speed and magnitude of disruption propagation; estimated of time (and cost) to recovery; identifying non-traditional response measures; and examining the appropriateness of traditional and non-traditional risk resilience measures, in varying disruption conditions.

Future research can also direct the discussion towards *intersecting SCs* which are intertwined and characterised by changing roles of companies within the network (e.g., one company can be a supplier in one SC, and a customer in another SC). Such types of networks add specific features to the resilience research. One useful concept could be multi-structural SC analysis (Ivanov et al., 2010, 2018b). Research on developing and querying AI and data driven SC digital twins can be furthered (e.g., Ivanov and Dolgui, 2020a).

3.3 Thinking ahead when the crisis ends: future research avenues on recovery after the pandemic and long-term SC re-designs

Finally, we look beyond the time of crisis and offer some sentiments on the recovery of SCs after the quarantine times. The simulations described in this paper have been done early March 2020 when the companies have dealt with predicting the COVID-19 impacts on the global SCs and performance. End of March, most of our assumptions and results have been con-firmed. Quarantines have been introduced worldwide affecting the downstream SC echelons and dropping the market demand with assumed delays between 30–60 days after the epidemic outbreak in China. Supply and demand have been drastically disrupted. Profits of man SCs dropped and the operations have been disrupted. Estimates of recovery time vary greatly (McKinsey, 2020).

The next step towards recovery may focus on questions such as:

- when to re-open facilities considering different quarantine times in different countries and even different states within the same country
- what is the best scale and timing to ramp-up OEM operations
- impact of quarantine lengths on recovery, short- and long-term performance.

Recovery is one of the major stages in SC resilience management (Sheffi and Rice, 2005; Blackhurst et al., 2011; Hosseini et al., 2019). In general, literature on recovery is rather scarce as compared to the state-of-the art on other SC resilience management stages, such as mitigation policies or resilient SC design. A recent review of SC recovery literature can be found in Ivanov et al. (2017). However, the topic of recovery after epidemic outbreaks has not been studied so far. The COVID-19 example clearly shows that the epidemic outbreaks represent a very specific and new setting for research in SC recovery. Moreover, the situation of partial or even full shut down of whole industry sectors and regions has never been considered. The analysis of post-disruption recovery has never been done for this unique set of components (Ivanov, 2020a; Ivanov et al., 2019a, 2019c). We consider it as opportunity to make substantial contributions. Such research can help companies to answer some urgent and survival-related questions, e.g.,

- Which suppliers should be re-opened and when to resume operation of OEM?
- Should we expedite the operation resuming at a particular supplier and at what time scale?
- What is the optimal scale of ramping-up given the forecasts of supplier and market re-openings?

Moreover, SCs in real life do not operate autonomously, but span and interconnect within and even across the business sectors. As noted by Vincenzo Boccia, the president of Confindustria in Italy on 23 March 2020 (Agi, 2020), it is very difficult to overcome the epidemic crisis and determine the most essential SCs to ensure survivability since "suppliers in the automotive sec-tor are at the same time producers of valves for respirators." The study by Ivanov and Dolgui (2020b) introduced in this regard two new concepts – the *intertwined supply network* (ISN) and *viability*. An ISN is an entirety of interconnected SCs which, integrate and secure society and markets with goods and services. The firms in ISNs may exhibit multiple behaviours by changing the buyer-supplier roles in interconnected or even competing SCs. The analysis of survivability at the level of ISN requires a consideration at a more expanded and complex scale relative to the resilience of individual SCs. ISNs as a whole provide services to society (e.g., food service, mobility service or communication service) that are necessary to long-term survival. The resilience and viability of ISNs has not received much attention in literature so far. The COVID-19 outbreak shows that in the case of extraordinary events, SC resistance to disruptions needs to be evaluated as an issue of civic and industrial survival, and not just SC profit or lead time performance. The example of Coronavirus COVID-19 outbreak clearly shows the necessity of this new perspective where substantial contributions can be done in future.

Undoubtedly, the COVID-19 crisis raises questions about the continued functioning of global SCs and possible future SC re-designs. We believe that this is not the end of global SCs. Every crisis ends, and once the situation normalises, global SCs would continue to offer a degree of efficiency and effectiveness that cannot be matched by domestic or regionally limited SCs. However, recent discussions with many SC managers point to localisation as a possible central topic of SC re-designs in two aspects:

- semi-active local supply base and markets
- offline local supply base and markets.

In the semi-active localisation, the major idea is to incorporate local suppliers and markets in the SCs in all daily business activities at some low or medium rate, e.g., 10–20% of the total supply and sales volume. In the case of a global crisis, such structures can be quickly scaled to 70–80% which would be beneficial both for suppliers, and OEMs, and markets.

The option of offline local supply base and markets does not presume any daily business activities with local suppliers and markets. However, the firms may consider maintaining in their planning systems 'virtual' local supply and demand structures for the cases of global crises. This would help to quickly re-design the SCs in the disruption case.

In both options above, the issues of capacity flexibility and product diversification should be considered. For example, a flexible capacity could allow to quickly change the manufacturing technology to produce the goods which are in demand in the markets that remain available.

Acknowledgements

This research has been partially funded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 873077 (MAIA-H2020-MSCA-RISE 2019).

References

Agi (2020) *L'economia di Guerra ci Costa 100 Miliardi al Mese*, Dice Boccia [online] https://www.agi.it/economia/news/2020-03-23/coronavirus-boccia-costo-economia-di-guerra-7773008/ (accessed 25 March 2020).

Altay, N. and Pal, R. (2014) 'Information diffusion among agents: implications for humanitarian operations', *Production and Operations Management*, Vol. 23, No. 6, pp.1015–1027.

Altay, N., Gunasekaran, A., Dubey, R. and Childe, S.J. (2018) 'Agility and resilience as antecedents of supply chain performance under moderating effects of organizational culture within humanitarian setting: a dynamic capability view', *Production Planning and Control*, Vol. 29, No. 14, pp.1158–1174.

Anparasan, A.A. and Lejeune, M.A. (2018) 'Data laboratory for supply chain response models during epidemic outbreaks', *Annals of Operations Research*, Vol. 270, Nos. 1–2, pp.53–64.

Blackhurst, J., Dunn, J. and Craighead, C. (2011) 'An empirically derived framework of global supply resiliency', *Journal of Business Logistics*, Vol. 32, No. 4, pp.347–391.

Choi, T-M., Wen, X., Sun, X. and Chung, S-H. (2019) 'The mean-variance approach for global sup-ply chain risk analysis with air logistics in the blockchain technology era', *Transportation Re-search Part E: Logistics and Transportation Review*, Vol. 127, pp.178–191.

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

Dasaklis, T.K., Pappis, C.P. and Rachaniotis, N.P. (2012) 'Epidemics control and logistics operations: a review', *International Journal of Production Economics*, Vol. 139, No. 2, pp.393–410.

Dolgui, A., Ivanov, D. and 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*, Vol. 58, No. 5, pp.1285–1301.

Dolgui, A., Ivanov, D. and Sokolov, B. (2018) 'Ripple effect in the supply chain: an analysis and recent literature', *International Journal of Production Research*, Vol. 56, Nos. 1–2, pp.414–430.

Dubey, R., Gunasekaran, A. and Papadopoulos, T. (2019) 'Disaster relief operations: past, present and future', *Annals of Operations Research*, Vol. 283, Nos. 1–2, pp.1–8.

Esra Büyüktahtakın, İ., des-Bordes, E. and Kıbış, E.Y. (2018) 'A new epidemics-logistics model: insights into controlling the Ebola virus disease in West Africa', *European Journal of Operational Research*, Vol. 265, No. 3, pp.1046–1063.

Fahimnia, B., Jabarzadeh, A. and Sarkis, J. (2018) 'Greening versus resilience: a supply chain design perspective', *Transportation Research – Part E*, Vol. 119, pp.129–148.

Farahani, R.Z., Lotfi, M.M. and 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.

Green, L.V. (2012) 'OM forum – the vital role of operations analysis in improving healthcare delivery', *Manufacturing & Service Operations Management*, Vol. 14, No. 4, pp.488–494.

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

ISM (2020) [online] https://weareism.org/coronavirus-ism.html (accessed 28 March 2020).

Ivanov, D. (2017) 'Simulation-based single vs. dual sourcing analysis in the supply chain with consideration of capacity disruptions, big data and demand patterns', *International Journal of Integrated Supply Management*, Vol. 11, No. 1, pp.24–43.

Ivanov, D. (2018a) 'Revealing interfaces of supply chain resilience and sustainability: a simulation study', *International Journal of Production Research*, Vol. 56, No. 10, pp.3507–3523.

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

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*, Vol. 127, pp.558–570.

Ivanov, D. (2020a) ''A blessing in disguise' or 'as if it wasn't hard enough already': reciprocal and aggravate vulnerabilities in the supply chain', *International Journal of Production Research* [online] https://doi.org/10.1080/00207543.2019.1634850.

Ivanov, D. (2020b) '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*, forthcoming.

Ivanov, D. and Dolgui, A. (2019) 'Low-certainty-need (LCN) supply chains: a new perspective in managing disruption risks and resilience', *International Journal of Production Research*, Vol. 57, Nos. 15–16, pp.5119–5136.

Ivanov, D. and Dolgui, A. (2020a) 'A digital supply chain twin for managing the disruptions risks and resilience in the era of Industry 4.0', *Production Planning and Control*, forthcoming.

Ivanov, D. and Dolgui, A. (2020b) '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*, DOI:10.1080/00207543.2020. 1750727.

Ivanov, D. and Rozhkov, M. (2017) 'Coordination of production and ordering policies under capacity disruption and product write-off risk: an analytical study with real-data based simulations of a fast moving consumer goods company', *Annals of Operations Research* [online] https://doi.org/10.1007/s10479-017-2643-8.

Ivanov, D., Dolgui, A. and Sokolov, B. (2019a) 'The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics', *International Journal of Production Research*, Vol. 57, No. 3, pp.829–846.

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

Ivanov, D., Dolgui, A., Das, A. and Sokolov, B. (2019c) 'Digital supply chain twins: managing the ripple effect, resilience and disruption risks by data-driven optimization, simulation, and visibility', in Ivanov, D. et al. (Eds.): *Handbook of Ripple Effects in the Supply Chain*, pp.309–332, Springer, New York.

Ivanov, D., Dolgui, A., Sokolov, B. and Ivanova, M. (2017) 'Literature review on disruption recovery in the supply chain', *International Journal of Production Research*, Vol. 55, No. 20, pp.6158–6174.

Ivanov, D., Sokolov, B. and Dolgui, A. (2014) 'The ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management', *International Journal of Production Research*, Vol. 52, No. 7, pp.2154–2172.

Ivanov, D., Sokolov, B. and Kaeschel, J. (2010) 'A multi-structural framework for adaptive supply chain planning and operations control with structure dynamics considerations', *European Journal of Operational Research*, Vol. 200, No. 2, pp.409–420.

Ivanov, D., Tsipoulanidis, A. and Schönberger, J. (2019d) 'Global supply chain and operations management: a decision-oriented introduction into the creation of value', *Springer Nature*, 2nd ed., Cham.

Kinra, A., Ivanov, D., Das, A. and Dolgui, A. (2019) 'Ripple effect quantification by supply risk exposure assessment', *International Journal of Production Research*, forthcoming.

Koyuncu, M. and Erol, R. (2010) 'Optimal resource allocation model to mitigate the impact of pandemic influenza: a case study for Turkey', *Journal of Medical Systems*, Vol. 34, No. 1, pp.61–70.

Lee, E.K., Smalley, H.K., Zhang, Y. and Pietz, F. (2009) 'Facility location and multi-modality mass dispensing strategies and emergency response for biodefence and infectious disease outbreaks', *International Journal of Risk Assessment and Management*, Vol. 12, No. 2, pp.311–351.

Mamani, H., Chick, S.E. and Simchi-Levi, D. (2013) 'A game-theoretic model of international influenza vaccination coordination', *Management Science*, Vol. 59, No. 7, pp.1650–1670.

McKinsey (2020) *Global Surveys of Consumer Sentiment during the Coronavirus Crisis* [online] https://www.mckinsey.com/business-functions/marketing-and-sales/our-insights/global-surveys-of-consumer-sentiment-during-the-coronavirus-crisis?cid=other-eml-alt-mip-mck&hlkid=9e25e97ea8d949b1a64ce769e428860c&hctky=2055019&hdpid=8360a4aa-fe3e-47a9-9f27-4105cb85fc46 (accessed 27 March 2020).

Pavlov, A., Ivanov, D., Pavlov, D. and Slinko, A. (2019a) '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. and Sokolov, B. (2019b) '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.

Schmidt, W. and Simchi-Levi, D. (2013) *Nissan Motor Company Ltd.: Building Operational Resiliency* [online] https://mitsloan.mit.edu/LearningEdge/operations-management/nissan-motor-company/Pages/default.aspx (accessed 20 March 2020).

Sheffi, Y. and Rice Jr., J.B. (2005) 'A supply chain view of the resilient enterprise', *MIT Sloan Management Review*, Vol. 47, No. 1, pp.41–48.

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

Tomlin, B. (2006) 'On the value of mitigation and contingency strategies for managing supply chain disruption risks', *Management Science*, Vol. 52, pp.639–657.

Xu, S., Zhang, X., Feng, L. and Yang, W. (2020) 'Disruption risks in supply chain management: a literature review based on bibliometric analysis', *International Journal of Production Research*, DOI: 10.1080/00207543.2020.1717011.