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Viability of Intertwined Supply Networks: Extending the Supply Chain Resilience Angles towards Survivability. A Position Paper Motivated by COVID-19 Outbreak

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Abstract: An intertwined supply network (ISN) is an entirety of interconnected supply chains (SC) which, in their integrity secure the provision of society and markets with goods and services. The ISNs are open systems with structural dynamics since the firms may exhibit multiple behaviors by changing the buyer-supplier roles in interconnected or even competing SCs. From the positions of resilience, the ISNs as a whole provide services to society (e.g., food service, mobility service or communication service) which are required to ensure a long-term survival. The analysis of survivability at the level of ISN requires a consideration at a large scale as resilience of individual SCs. The recent example of coronavirus COVID-19 outbreak clearly shows the necessity of this new perspective. Our study introduces a new angle in SC resilience research when a resistance to extraordinary disruptions needs to be considered at the scale of *viability*. We elaborate on the integrity of the ISN and viability. The contribution of our position study lies in a conceptualization of a novel decision-making environment of ISN viability. We illustrate the viability formation through a dynamic game-theoretic modelling of a biological system that resembles the ISN. We discuss some future research areas.

Keywords: supply chain resilience; supply chain risk management; supply chain dynamics; intertwined supply network; viability; survival; coronavirus (COVID-19)

1. Introduction

Coronavirus COVID-19 outbreak is an unprecedented and extra-ordinary situation that clearly shows a need for progressing the supply chain (SC) resilience research and practices. The coronavirus outbreak affects the global and local economies at a larger scale. Supply availability in global SCs has been drastically reduced and misbalanced with the demands. According to Araz et al. (2020), the COVID-19 dispersal “*is breaking many global SCs*”. Early in March 2020, the number of COVID-19 cases has grown exponentially all over the world resulting in border closures, quarantines, and entirely full shut downs of many crucial facilities, markets and activities in the SCs. On March 11, 2020, the World Health Organization (WHO) announced the global pandemic.

Being lean and globalized in structures, the SCs of many companies became specifically prone to coronavirus outbreaks (Ivanov 2020). 94% of the Fortune 1000 companies have been affected by coronavirus-driven SC disruptions (Fortune 2020). Linton and Vakil (2020) show on the example of data from the Resilinc system that the world’s largest 1,000 SCs own more than 12,000 facilities (i.e., factories, warehouses and other operations) in COVID-19’s quarantine areas. For some SCs, demand has drastically increased and the supply was not able to cope with that situation (e.g., facial masks, hand sanitizer, disinfection spray). As such, the question of market and society survivability was raised. For other SCs, the demand and supply have drastically dropped resulting in the production stops (e.g., automotive industry), the danger of bankruptcies and necessities of governmental supports (Harbour 2020). Here, the questions of SC survivability arose. Obviously, both these questions go beyond the existing state-of-the-art in SC resilience since they cannot be resolved within a narrow SC perspective but rather require an analysis at a larger scale.

One interesting research avenue to bring the discussion at the level of survivability is to consider the concept of *viability*. While SC resilience has gained a considerable attention (Dolgui et al. 2020, Hosseini et al. 2019), the understanding of viability remains an open research question. In this paper, we define *viability as the system ability to meet the demands of surviving in a changing environment* following the Viable System Model by Beer (1981) and ecology modeling perspectives (Aubin 1991). The example of coronavirus COVID-19 outbreak shows that in case of extraordinary events, SC resistance to disruptions needs to be considered at the scale of survivability or viability to avoid SC and market collapses and secure the provision with goods and services.

Analysis of the viability concepts in ecology, biological systems (Aubin 1991) and cybernetics (Beer 1981) shows that viability is mostly considered in the settings of complex systems which span and connect some individual sub-systems. In SC domain, several examples of such systems can be observed in literature and practice. Niu et al. (2019) show that Apple and Samsung play the role of both suppliers and competing focal firms in two different but intersecting SCs. Wang (2014) and Wang et al. (2019) develop the concept of holistic SC networks that are composed of a group of intersecting SCs which are intertwined. The SC intertwining can also be encountered in industrial symbiosis as well as in circular and sharing economies (Fracassia et al. 2017, Choi et al. 2020). Another example is a symbiosis of commercial and humanitarian logistics when several business and humanitarian SCs are sharing the warehouse facilities (Altay and Green 2006, Dubey and Altay 2018, Dubey et al. 2019b). Considering the practical environments, Kelly and Marchese (2015) point to “*complex, dynamic, interconnected supply chains*” highlighting to the role of information technology in synchronizing the SCs within the

value webs. As noted by Vincenzo Boccia, the president of Confindustria in Italy on March 23, 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 sector are at the same time producers of valves for respirators”.

Despite the existence and an increasing practical utilization of the above concepts, the SC management literature has not framed this new kind of network integrities in a specific concept so far. In this study, we introduce for the first time the term “*Intertwined Supply Network*” (ISN) that encapsulates *entireties of interconnected SCs which, in their integrity secure the provision of society and markets with goods and services*. While the resilience is related to the level of individual SCs or supply networks, viability is considered at the ISN level. SCs rarely represent single, isolated networks but are rather open systems that are characterized by structural dynamics (Ivanov et al. 2010, Kelly and Marchese 2015). In contrast to linearly directed SCs or supply networks (cf. Fig. 1) with static structures, the firms in the ISNs may exhibit multiple behaviors in buyer-supplier relations (i.e., behavioral dynamics) being buyers and suppliers in interconnected or even competing SC simultaneously.

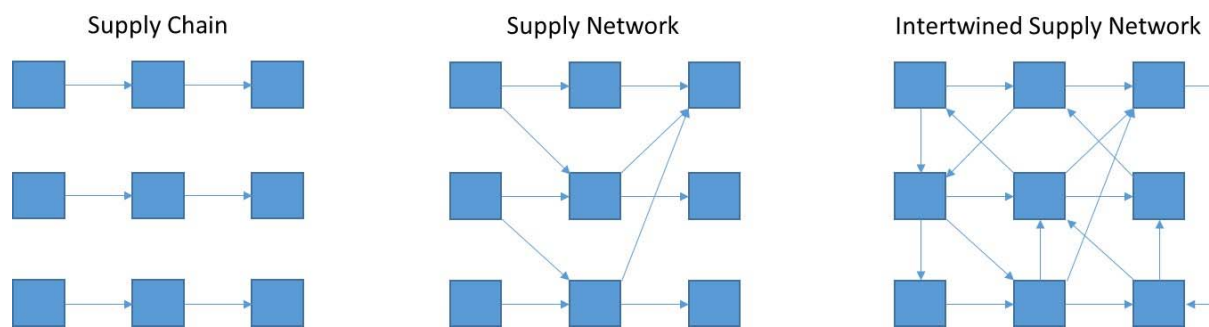


Fig. 1. Linear supply chains, supply networks and intertwined supply networks

The assumption that the firms’ roles in the SCs can vary might change the kind of problem settings and results to be expected from the analysis of system properties closed to resilience. Differently but supplementing to the studies on SC resilience, we consider in this paper the *ISN viability*. From the positions of resilience, the ISNs as a whole provide services to society (e.g., food service, mobility service or communication service) which are required to ensure a long-term survival. The analysis of survivability at the level of ISN requires a consideration at a large scale as resilience of individual SCs. The recent example of coronavirus COVID-19 outbreak clearly shows the necessity of this new perspective.

For example, a traditional understanding of automotive SCs is the car production as the final output goal. Differently, the ultimate goal of an automotive ISN is to provide a mobility service to society. In electronics industry, a traditional SC understanding yields production of some electronic devices as a desired output performance while the performance of the electronics ISN is rather related to providing communication service to society. As such automotive and electronics ISNs are responsible to provide to important services to society, i.e., mobility and communication at a global scale. Obviously, the analysis of disruption impacts at such a level is concerned with long-term securing the mobility and communication in the society, i.e., ensuring the *viability*, rather than with performance impact of disruptions in individual SCs in terms of revenue or annual sales, as traditional SC resilience analysis usually does.

Therefore, the ISN viability appears a timely and crucial topic which opens doors for a variety of new problem settings and solution techniques. The global pandemic and SC collapses moved

the SC survivability issues through collective behavioral changes in the forefront of risk management discussions (Keogh 2020, Ivanov 2020). The SC survivability in the context of such extra-ordinary events goes beyond a narrow understanding of SC performance as some profits or revenues and brings the discussion to the next level, i.e., SC performance in terms of securing the provision of the goods and services in society and long-term survival of the whole industry sectors.

The contribution of this position paper lies in conceptualization of a novel decision-making environment for SC resilience that considers ISN and viability as an integrity. Our study introduces a new angle in SC resilience research when SC resistance to extraordinary disruptions needs to be considered at the scale of survivability, or *viability*. We also illustrate the viability concept idea through a dynamic game-theoretic modelling inspired from a biological system that resembles the ISN. We discuss some future research areas. Conceptually, in Section 2 we show how viability is different than the resilience, and why viability appears a necessary quality to be added to the SC resilience analysis in the ISN context. Technically, building upon the resemblance of ISN to ecological systems, we illustrate in Section 3 the viability formation through dynamic game-theoretic modelling of a biological system. Section 4 is devoted to the discussion of theoretical and practical implications as well as future research avenues. We summarize in Section 5 the main ideas of the paper.

2. Literature review

In this section, we discuss recent literature on SC resilience in the aspects concerned with viability. Since there is no specific literature on SC viability, we consider the state-of-the-art SC resilience angles as the most appropriate methodical basement for a development of the viability concept.

2.1. Viability vs. stability, robustness, and resilience of SCs

To recapitulate, *Viability* is a system ability to meet the demands of surviving in a changing environment. SC literature has produced a large body of knowledge for analysis of network behaviors and their adaptations in the presence of changing environments which are related to the categories of stability, robustness, and resilience. Therefore, we present these concepts here and compare with each other. Our analysis remains at a generalized level according to the objective of this position paper, and we refer the interested reader to the survey papers by Ho et al. (2015), Ivanov et al. (2017), Dolgui et al. (2020), Bier et al. (2019), DuHadway et al. (2019), Hosseini et al. (2019), for more detailed considerations.

Put simply, SC reaction to disturbances can be analysed as follows (Table 1):

- Stability – ability to return to a pre-disturbance state and ensure a continuity (Ivanov and Sokolov 2013, Demirel et al. 2019)
- Robustness – ability to withstand a disruption (or a series of disruptions) to maintain the planned performance (Nair and Vidal 2011, Simchi-Levi et al. 2018)
- Resilience – ability to withstand a disruption (or a series of disruptions) and recover the performance (Spiegler et al. 2012, Hosseini et al. 2019).

Table 1: Major analysis concepts for SC performance under uncertainty

Concept	Operational disturbance	Disruption in SC structures	Output performance	Recovery	Survivability
Stability	+				
Robustness	+	+	+		
Resilience		+	+	+	
Viability		+	+	+	+

Demirel et al. (2019) point to stability as a “basic desirable property of a supply network without an explicit consideration of performance” while the robustness and resilience explicitly include the performance in the analysis of disruption impacts. Ivanov and Sokolov (2013) show that robustness allows to analyse the system ability to withstand a disruption (or a series of disruptions) without any structural and parametrical changes/adaptations, while resilience analysis explicitly allows the system to employ some recovery/adaptation in order to restore the disrupted operations and performance (Craighead et al. 2007, Zhao et al. 2019).

Research in SC reaction to disturbances is related to the semantic network analysis level with a focus on structural properties, complexity roles, and node/arc criticality (Ivanov and Dolgui 2019). The studies (Basole and Belami 2014, Ivanov et al. 2014a,b, Kim et al. 2015, Brintrup et al. 2016, Sawik 2017, Machdonald et al. 2018, Yoon et al. 2018, Scheibe and Blackhurst 2018, Pavlov et al. 2018, Ojha et al. 2018, Giannoccaro et al. 2017, Ivanov 2018, 2019, Dolgui et al. 2018, Li et al. 2019, Pavlov et al. 2019b) recognized the structural SC properties as crucial determinant to maintain stability and robustness and to achieve resilience. Another important observation in literature is a linkage of SC complexity and resilience (Blackhurst et al. 2005, Nair and Vidal 2011, Bode and Wagner 2015, Dubey et al. 2019a, Tan et al. 2020). Ivanov and Dolgui (2019) emphasize that complex networks become more vulnerable to severe disruptions which change the SC structures and are involved with SC structural dynamics. Finally, node/arc criticalities in SCs have attracted attention of researchers. Basole and Bellamy (2014) focused on the identification of “healthy nodes” in the SC based on the level of risk diffusion. Chen et al. (2017) and Macdonald et al. (2018) show that SC robustness and resilience should not merely be based on a straightforward disruption magnitude analysis, but rather seek trajectories of how different disruption scenarios influence the severity in network degradation and recovery (Pavlov et al. 2019a).

The term “viability” has been widely used in ecological modelling (Aubin 1991, Bene et al. 2001) *as a system ability to maintain itself and recover in the presence of disturbances over a long-term horizon*. In Table 2, we summarize the major differences between the resilience and viability.

Table 2 Differences Resilience vs. Viability

Criterion	Resilience	Viability
System	Close	Open
Structure	Static	Dynamic
Scope of analysis	Disruption-driven (single, discrete, unique events)	Behavior-driven (continuous change)

Subject of analysis	Discrete, singular disruption-reaction analysis within a closed system setting	Continuous evolution through disruption-reaction balancing in the open system context
Target of analysis	Performance-oriented	Survival-oriented
Period of analysis	Fixed time-window	No fixed time window
Object of analysis	Linear supply chain system	Intertwined supply networks / supply chain ecosystems

To this end, resilience is considered a disruption-driven SC property (single, discrete, unique events). It relates to singular disruption-reaction analyses within a closed system setting. These analyses are performance-oriented for some fixed time-windows and mostly linear, single-flow directed SC systems. Viability is a behavior-driven property (continuous system change) of a system with structural dynamics. It considers system evolution (i.e., open system context) through disruption-reaction balancing in the open system context. The viability analysis is survival-oriented without fixed time windows at a long-term scale.

2.2. Intertwined supply networks (ISN)

In this study, we consider ISNs, i.e. complex supply networks with dynamically changing structures, roles and behaviors of the firms involved. For example, Zhao et al. (2019) show that a competitor of a focal firm can also serve as the focal firm's upstream supplier echoed by Niu et al. (2019) who consider a co-opetition SC setting on the example of Apple and Samsung with a competitive supplier (i.e., frenemy) that plays the role of both supplier and competing focal firm in two different but intersecting SCs simultaneously causing dependence asymmetry (Dong et al. 2015).

In early 2000s, the ideas of dynamic SC formations have found first developments in the area of virtual enterprises and collaborative networks (Ivanov et al. 2004, 2005, Camarinha-Matos and Afsarmanesh 2005, Dekkers 2009, Ivanov et al. 2009, Sarkis et al. 2007, Dolgui and Proth 2010, Ivanov and Sokolov 2012, Chibani et al. 2018). Other relevant research streams can be found in the theories of complex adaptive systems (Choi et al. 2001, Surana et al. 2005) and SC structural dynamics (Ivanov et al. 2010).

Most recently, Fracassia et al. (2017) point to the multiple, intersecting SCs in the industrial symbiosis which are characterized by using the waste of some SC processes as the inputs into the other SCs (Pathak et al. 2014). Olson et al. (2018) elaborate on the intelligence-connected manufacturing. Moreover, Industry 4.0 and cyber-physical manufacturing have significantly transformed the SCs and increased their intertwining (Liao et al. 2017, Ivanov et al. 2019, Panetto et al. 2019, Tang and Veelenturf 2019). Choi et al. (2020) show different forms of SC interconnections in the sharing and circular economies. As such, we can conclude that many SCs evolve into ISNs based on the principles of co-creation and co-evolution. Such mechanisms are principally different from the classical SC understanding and therefore it becomes a timely and crucial research task to develop a new thinking of resilience towards viability.

Moreover, analyses from the value point of view are often applied. A possible new way for the research from viability perspectives deals with the value web approaches developed, for example by Amazon. A value web is based on the use of highly synchronized information technologies to coordinate value chains of different firms of ISN (Kelly and Marchese 2015).

2.3. ISN analysis inspired from ecology modeling

ISNs in this context can be studied with approaches similar to ecological modelling. Ecological modelling is a research area concerned with the analysis of ecosystems in dynamics (Gross et al. 2004, 2009). Recent literature point to resemblance of the SCs to ecosystems (Byrne et al. 2018, Gross et al. 2018, Demirel et al. 2019, Nair and Reed-Tsochas 2019). The applications of ecological modelling to SC uncertainty have been mostly focused on the stability analysis and multi-echelon SC synchronization in terms of balancing the demand and inventory levels (Anne et al. 2009, Demirel et al. 2019, Mondal et al. 2019).

Ecological perspective of the resilience has been developed by Holling (2006) which is based on the ability of system to react to stressors, to absorb and withstand shocks, with an emphasis on persistence. We consider ecological perspective as the closest one to SC viability since it focuses on the ecosystem services provided to society (Linkov and Kott 2019).

Major principles of ecology modeling are survival-orientation, absence of explicit time windows in analysis, and ecosystem focus. These principles appear to be very close to the ISN viability (cf. Sect. 2.1). We note that viability does not replace resilience but rather adds a new quality to analysis of SC performance and behaviors under uncertainty.

3. Trophic chain-based model of the ISN viability

In this section, we illustrate the viability formation in networks by an original interpretation of a three-level trophic chain model developed in the area of ecological modelling (Aubin 1991, Bonneuil and Saint-Pierre 2005). We note that this model is presented in our study to illustrate the concept of viability rather than to be used as an optimization tool for a particular decision-making setting. Our interpretation comprehensively combines major determinants of the ISNs, i.e., competition between suppliers, market demands, and behavioral dynamics.

3.1 Trophic chain

Trophic chains are a part of ecological modelling. Conceptually, trophic chains are used for modeling and analysis of prey-predator systems. Technically, the trophic chain modelling is rooted into the Lotka–Volterra first-order nonlinear differential equations, also known as the predator–prey equations (Getz et al. 2003, Baudrot et al. 2018).

The system of differential equations describes the trophic chain dynamics subject to some functional response (i.e., the consumption rate of the predator depending on the density rate of the preys) and interactions between the prey and predator. The Jacobian matrix of the predator–prey model can be used to analyse the stability of the ecological system and the impact of oscillations (Gross et al. 2004). Moreover, the bifurcation point analysis makes it possible to observe the disturbance propagation through the trophic chain, i.e., the cascading effect (Baudrot et al. 2018) and to identify the timing when the ecosystem will turn into a chaotic state under the given dynamics (Dilao and Domingos 2000, Gross et al. 2009, Castellanos and Chan-Lopez 2017).

It can be observed that the trophic chain exhibits some characteristics close to the SC. In literature, SCs are considered multi-stage systems which dynamics is guided through vendor-buyer operations. Generally, a firm that plays the buyer role in an upstream echelon of the supply chain becomes a supplier in the next downstream stage. We take up this observation of commonalities between the trophic chains and the SCs and bring the discussion to the next level by using the trophic chain concept for viability analysis of the ISNs.

3.2. Model

We illustrate the viability formation in an ISN through dynamic game-theoretic modelling of an ecosystem. Game-theoretical models have been considered suitable to address the SC disruption risks analysis (Gupta and Ivanov 2020). We follow the model of Bonneuil and Saint-Pierre (2005) rooted in population viability analysis as a method of risk assessment frequently used in conservation biology. We describe the viability of an ISN where firms exhibit independent, time-varying survival strategies by a specific set, the viability kernel, gathering all states from which there exists at least one trajectory safeguarding each firm over a given survivability threshold (e.g., minimal levels of some financial or operational indicators which allow maintaining the firm's operations and avoiding bankruptcy).

Consider an ISN structure (Fig. 2).

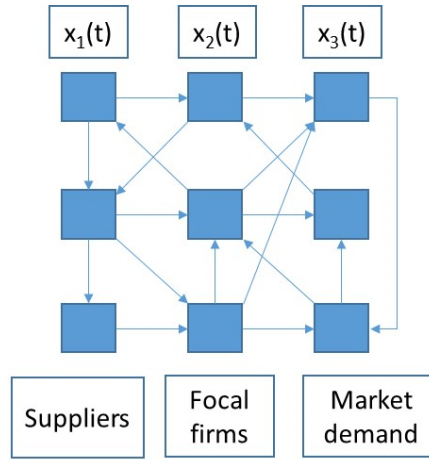


Fig 2. Intertwined supply network modelling

In an ISN ecosystem, three major roles can be distinguished, i.e., suppliers, focal firms, and market demand, i.e., the consumers. Notably, the firms can play different roles simultaneously. As such, if we talk about a supplier, we do not mean a concrete firm but rather a role in a particular SC that can be taken by different firms situationally.

Denote inventories at suppliers, focal firms, and markets (customers) as vector functions $x_1(t)$, $x_2(t)$, $x_3(t)$, respectively. Eqs. (1)-(3) represent the dynamics of firm interactions and can be considered as a dynamical game (Bonneuil and Saint-Pierre 2005) where supplier, focal firm and customer constitute the three players, and where $u(t) \in [u_{min}, u_{max}] = U$, $v(t) \in [v_{min}, v_{max}] = V$, and $w(t) \in [w_{min}, w_{max}] = W$ represent the respective behavioral strategies of suppliers, focal firms, and customers.

$$x'_1(t) = x_1(t)(1 - u(t)x_1(t) - v(t)x_2(t)) := f_1(x(t), u(t), v(t), w(t)) \quad (1)$$

$$x'_2(t) = x_2(t)(v(t)x_1(t) - w(t)x_3(t)) := f_2(x(t), u(t), v(t), w(t)) \quad (2)$$

$$x'_3(t) = x_3(t)(w(t)x_2(t)) := f_3(x(t), u(t), v(t), w(t)) \quad (3)$$

The dynamical game (1)-(3) consists in having the system change so that the firms in an ISN can keep the possibility to survive jointly by selecting such strategies that allow each player to continue playing the game, i.e., to survive. In the setting of coronavirus COVID-19 pandemic, the strategies $u(t) \in [u_{min}, u_{max}] = U$, $v(t) \in [v_{min}, v_{max}] = V$, and $w(t) \in [w_{min}, w_{max}] = W$ would mean some operating policies (e.g., inventory control) at firms of different SC echelons. $u(t)$ describes the strategies at the suppliers. $v(t)$ and $w(t)$ describe the

buyer and customer strategies, respectively. Technically, the game consists in safeguarding a least one solution of the system (1)-(3) that can be written into the differential inclusion (4)

$$x'(t) \in F(x(t)) \quad (4)$$

under constraint (5)

$$x(t) \in K \quad (5)$$

remaining in a fixed closed set K , where

$$F(x(t)) := \{f(x, u, v, w) | u(t) \in U, v(t) \in V, w(t) \in W\} \quad (6)$$

is a point-to-set map, also called correspondence.

The set K describes the strategies for co-existence of the entities in the ISN. The set K is viable if suppliers, focal firms and markets are maintain themselves above certain thresholds and are able to co-exist under these conditions. In other words, there exists at least one solution $x(\bullet) = (x_1(\bullet), x_2(\bullet), x_3(\bullet))$ of the dynamical game (1)-(3) starting from x^0 and satisfying the threshold conditions. The viability kernel of the set \tilde{K} is the largest closed viable set in K under the dynamic F (Eq. 6) that represents the integrity of survival strategies for the firms in the ISN. According to Aubin (1991) and Bonneuil and Saint-Pierre (2005), the strategies permitting the property (7):

for all $x(t) \in \tilde{K}$ there exists $u(t) \in U, v(t) \in V, w(t) \in W$

such that

$$\{f_1(x, u, v, w), f_2(x, u, v, w), f_3(x, u, v, w) \in T_{\tilde{K}}(x)\} \quad (7)$$

can be called viable strategies of the ISN, where $T_{\tilde{K}}(x)$ is the contingent cone at state x . All the solutions outside the viability kernel lead to loss of either internal competition between suppliers, or behavioral dynamics, or market demand fulfilment. Moreover, the viability approach make it possible to highlight the timing when the strategy change is needed for an ISN to perpetuate itself.

4. Discussion and implications for future research

Stability, robustness, and resilience analysis have covered a large area of SC disruption risk analysis. Though, none of them deals with ISNs mostly assuming directed network graphs and fixed time-window for analysis. While the resilience analysis of individual SCs is useful for many cases, the firms are participating in different SCs in different roles. This makes it an important research task to model the ISNs and not the individual SCs to correctly understand the impacts of disruptions and the ripple effects on the viability in the presence of extraordinary events. As such, a new terminology is obviously required.

We suggested using the term “viability” differently than the resilience in regard to the ISNs, in analogy to ecological modelling (Aubin 1991, Bene et al. 2001) that considers *viability as a system ability to maintain itself and recover in the presence of disturbances over a long-term horizon*.

In future, different topics of the ISNs in connection with viability can frame an interesting research avenue. Potential topics include but are not limited to:

- Framing the ISN viability and SC survivability concepts
- Network structures of ISNs and their viability
- Roles and dynamics of ISNs at the times of epidemic outbreaks

- Contributions of ISNs to recover the SCs after an epidemic outbreak
- How long can an ISN sustain a disruption so what is the critical disruption time?
- What are the most critical scenarios of epidemic propagation for the global SCs and their ISNs?
- Impact of digitalization, Big Data analytics, and additive manufacturing on the ISN viability
- Viability in the context of Value Web approaches
- Ripple effect in the ISNs
- Game-theoretic modelling of the ISN viability
- Complex adaptive systems with applications to ISNs
- Collaboration of humanitarian and business logistics for survivability
- Ecological modelling approaches to ISN viability
- Dynamic analysis of the ISN viability (simulation, control theory)

We use the example of coronavirus (COVID-19) outbreak to describe some future research angles. The global pandemic and collapses of many SCs and the markets depict the importance of the SC viability research. While the firms have increasingly dealt with the resilience of their global SCs triggered by some severe natural and man-made disasters and established a set of useful methods such as risk mitigation inventories, subcontracting capacities, backup supply and transportation infrastructures, and data-driven, real-time monitoring and visibility systems, it is unclear how these methods can be applied to SC survivability analysis.

One can expect that some of the SC resilience actions established to cope with natural disruptions can be useful for the viability analysis, too. Though, one can also expect that the specific features of viability would require an examination of new concepts or a modification of the existing ones. For example, the cases of epidemic disruptions, proactive measures such as inventory can help only at the beginning of the crisis due to very long disruption times. Backup suppliers and subcontracting facilities can also be supposed to be less efficient because of quarantining the whole regions and even continents. As such, our sentiment is that the focus of SC viability management would rather be shifted towards the situational reactions to real-time changes rather than building some proactive redundancies. At the same time, the importance of proactive management does not disappear. Here the focus would be shifted towards creating a *flexible redundancy* which would make the SC networks less sensitive to external uncertainties.

One research area in this direction is the LCN (low-certainty-need) SC framework (Ivanov and Dolgui 2019). In addition, the viability goes beyond a narrow understanding of SC performance as some profits or revenues and brings the discussion to the next level, i.e., SC performance in terms of securing the life on the earth. As such, the issues of collaborative, collective survival in the presence of extra-ordinary conditions are very important, and new research areas.

Some other open questions to address are, e.g.: *How to analyse disruption impacts in ISNs? How to analyse disruption propagation, i.e., the ripple effect in ISNs?* We note that even if viability is important, the questions of resilience, robustness and stability in ISNs are of equal importance as in the SC settings.

The concept and techniques for analysis and modeling of complex ecological networks as postulated by viability and trophic chains can find several applications to production and SC management and can stimulate some new ideas and research in SCs. The ecological modeling in general and trophic chains in particular have a potential to be applied to different areas of SC decision-making, such as:

- Risk propagation analysis in the SCs (e.g., bullwhip effect (propagation upstream) and ripple effect (propagation downstream))
- Quality management control (i.e., how a quality error propagates downstream the SC)
- Circular economy (i.e., cycles control)
- Competition modeling (survival competition, agent modeling, learning agents, learning through evolution).

At the same time, some potential limitations need to be addressed. A direct usage of mathematics for trophic chain analysis (i.e., non-linear dynamic differential system, bifurcation points) requires a specific technical competence which is not a standard equipment of SC and operations management researchers. Besides, the analysis of the ecological system frequently results in bifurcation points derivation of which can be difficult for large-scale system. Methodically, the bifurcation point analysis does not bring new insights into the recovery optimization. This analysis ends with the insight if we loss resilience or not, and we can also understand the conditions surrounding the resilience dynamics. Such an analysis of alternative paths the system takes to save resilience can be useful for deciphering the contingency plans. However, we do not go beyond the bifurcation point - this analysis is not much helpful for recovery and is therefore restricted to the pre-disruption stage and subject to very generalized flows. Such stylized models can certainly be of methodical interest; real system modelling will require simulations of complex adaptive systems and SC structural dynamics.

5. Conclusion

SCs evolve towards ISNs that are characterized by structural dynamics. Differently than linearly directed SCs with static structures, the firms in ISNs may exhibit multiple behaviors in buyer-supplier relations (i.e., behavioral dynamics) in interconnected or even competing SCs simultaneously. These new dynamic, co-evolving structures require re-thinking of some traditional analysis concepts.

An intertwined supply network (ISN) is an entirety of interconnected supply chains (SC) which, in their integrity secure the provision of society and markets with goods and services. Unlike the resilience of individual SCs, the viability of ISNs has not received much attention in literature so far. The recent example of coronavirus COVID-19 outbreak shows that in the case of extraordinary events, SC resistance to disruptions needs to be considered at the scale of survivability or viability to avoid SC and market collapses and secure the provision with goods and services. In this paper, we elaborated on the integrity of these two novel angles, i.e., ISNs and viability. The contribution of this study lies in conceptualization of a novel decision-making environment that considers ISNs and viability as an integrity to ensure the survivability at a large scale. We showed how the viability is different than the resilience, and why a necessary quality to be added to the SC resilience analysis in the context of ISNs ecosystems. Building upon the analogy of ISNs to ecological systems, we illustrated the viability formation through dynamic game-theoretic modelling of an ecosystem.

Some limitations exist in our approach, as with any study. We took a much generalized, “bird-eye” perspective on the viability and its modelling. For concrete applications, the concept of viability and the trophic chain modelling should be detailed and extended given the context of decision-making situations. In addition, the ISNs themselves need to be thoroughly investigated in terms of methodology and practice of their formations and control. Finally, the role of ISNs survivability in the securing the provision with goods and services in the case of extra-ordinary

events, such as epidemic outbreaks and global pandemics (e.g., coronavirus COVID-19). These areas can be considered promising future research avenues.

Another interesting research topic is examination of disruption outbreaks in the downstream SC parts and the resulting combined effects of the forward and backward propagations of the ripple effect. One promising research area in research on ISNs and their viability is the utilization of *digital, data-driven technologies* to uncover their potentials to support the decision-making in cases of long-term, severe disruptions such as epidemic outbreaks. In particular, digital SC twins (Ivanov and Dolgui 2020) – i.e., the computerized SC models that represent the network state for any given moment in real time – can be further investigated in this direction.

References

- Agi (2020). L'economia di guerra ci costa 100 miliardi al mese, dice Boccia. <https://www.agi.it/economia/news/2020-03-23/coronavirus-boccia-costo-economia-di-guerra-7773008/>, accessed on March 25, 2020.
- Altay, N., & Green, W. G. (2006). OR/MS research in disaster operations management. *European Journal of Operational Research*, 175(1), 475–493.
- Anne, KR., J. C. Chedjou & K. Kyamakya (2009). Bifurcation analysis and synchronisation issues in a three-echelon supply chain. *International Journal of Logistics Research and Applications* 12(5), 347-362.
- Araz, O.M., Choi, T.-M., Olson, D., Salman, F.S. (2020). Data Analytics for Operational Risk Management. *Decision Sciences*, forthcoming.
- Aubin J.P. (1991). *Viability Theory*, Birkhäuser, Boston, 1991.
- Basole, R.C. and Bellamy, M.A. (2014). Supply Network Structure, Visibility, and Risk Diffusion: A Computational Approach, *Decision Sciences*, 45(4), 1–49.
- Baudrot V., C. Fritsch, A. Perasso, M. Banerjee, F. Raoul (2018). Effects of contaminants and trophic cascade regulation on food chain stability: Application to cadmium soil pollution on small mammals – Raptor systems. *Ecological Modelling* 382, 33–42.
- Beer, S. (1981). *Brain of the firm*. Chichester: Wiley.
- Bene, C., L. Doyen, and D. Gabay (2001). A viability analysis for a bio-economic model. *Ecological Economics*, 36:385–396.
- Bier, T., Lange, A., & Glock, C. (2019). Methods for mitigating disruptions in complex supply chain structures: A systematic literature review. *International Journal of Production Research*. <https://doi.org/10.1080/00207543.2019.1687954>.
- Blackhurst, J., Craighead, C.W., Elkins D., and Handfield, R. (2005). An empirically derived agenda of critical research issues for managing supply-chain disruptions. *International Journal of Production Research*, 43(19), 4067-4081.
- Bode, C., S.M. Wagner, Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions, *Journal of Operations Management* 36, 215-228, 2015.
- Bonneuil N., P. Saint-Pierre (2005). Population viability in three trophic-level food chains. *Applied Mathematics and Computation* 169, 1086–1105.
- Brintrup, A., Y. Wang, and A. Tiwari (2015). Supply networks as complex systems: A network science-based characterization. *IEEE Systems Journal*, (99):1–12.
- Byrne, G. D Dimitrov, L Monostori, R Teti, F van Houten, R Wertheim (2018). Biologicalisation: Biological transformation in manufacturing. *CIRP Journal of Manufacturing Science and Technology* 21, 1-32.
- Camarinha-Matos, L.M. and Afsarmanesh, H. (2005) Collaborative networks: a new scientific discipline, *Journal of Intelligent Manufacturing*, 16, 439–452.

- Castellanos V., Chan-López RE (2017). Existence of limit cycles in a three level trophic chain with Lotka–Volterra and Holling type II functional responses. *Chaos, Solitons and Fractals* 95, 157–167.
- Chen, X., Z Xi, P Jing (2017) A Unified Framework for Evaluating Supply Chain Reliability and Resilience. *IEEE Transactions on Reliability*, 66(4), 1144 – 1156.
- Chibani A., Delorme X., Dolgui A., Pierreval H. (2018). Dynamic optimisation for highly agile supply chains in e-procurement context, *International Journal of Production Research*, 56 (17): 5904–5929.
- Choi T.-M., Taleizadeh A.A., Yue X. (2020). Game theory applications in production research in the sharing and circular economy era. *International Journal of Production Research*, 58(1), 118-127.
- Choi TY, Dooley KJ, Rungtusanatham M (2001) Supply networks and complex adaptive systems: control versus emergence. *J Oper Manag* 19(3):351–366
- Craighead, C.W., Blackhurst, J., Rungtusanatham, M.J. and Handfield, R.B. (2007), “The severity of supply chain disruptions: design characteristics and mitigation capabilities”. *Decision Sciences*, 38(1), 131-156.
- Dekkers, R. (2009). Distributed Manufacturing as Co-Evolutionary System. *International Journal of Production Research*, 47(8), 2031-2054.
- Demirel, G., MacCarthy, B.L., Ritterskamp, D., Champneys A. & Gross, T. (2019). Identifying dynamical instabilities in supply networks using generalized modeling. *Journal of Operations Management*, 65(2), 136-159.
- Dilao R., T. Domingos (2000). A general approach to the modelling of trophic chains. *Ecological Modelling* 132, 191–202.
- Dolgui A., Ivanov D., Sokolov B. (2018). Ripple effect in the supply chain: An analysis and recent literature. *International Journal of Production Research*, 56(1-2), 414-430.
- Dolgui A., Ivanov D., 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., Proth J.-M. (2010). *Supply chain engineering: Useful methods and techniques*, Springer.
- Dong, M. C., Z. Liu, Y. Yu, and J.-H. Zheng (2015). Opportunism in distribution networks: The role of network embeddedness and dependence. *Production and Operations Management* 24 (10): 1657–1670.
- DuHadway, S., Carnovale, S., & Hazen, B. (2019). Understanding risk management for intentional supply chain disruptions: Risk detection, risk mitigation, and risk recovery. *Annals of Operations Research*, 283(1–2), 179–198.
- Dubey, R., & Altay, N. (2018). Drivers of coordination in humanitarian relief supply chains. In G. Kovács, K. Spens, & M. Moshtari (Eds.), *The Palgrave handbook of humanitarian logistics and supply chain management* (pp. 297–325). London: Palgrave Macmillan.
- Dubey R., Gunasekaran A., Childe, S. J. Wamba S.F., Roubaud D., Foroqon C. (2019a). Empirical Investigation of Data Analytics Capability and Organizational Flexibility as Complements to Supply Chain Resilience. *International Journal of Production Research*, <https://doi.org/10.1080/00207543.2019.1582820>
- Dubey, R., A. Gunasekaran, T. Papadopoulos (2019b). Disaster relief operations: past, present and future. *Annals of Operations Research* 283 (1-2), 1-8
- Fortune (2020). <https://fortune.com/2020/02/21/fortune-1000-coronavirus-china-supply-chain-impact/>, accessed on March 10, 2020
- Fracassia L., Giannoccaro I., Albino V. (2017). Rethinking Resilience in Industrial Symbiosis: Conceptualization and Measurements. *Ecological Economics*, 137, 148-162.
- Getz W.M., H. V. Westerhoff, J.H. S. Hofmeyr, J. L. Snoep (2003). Control analysis of trophic chains. *Ecological Modelling* 168, 153–171.
- Giannoccaro I., Nair A., Choi T. (2017). The Impact of Control and Complexity on Supply Network Performance: An Empirically Informed Investigation Using NK Simulation Analysis. *Decision Science*, 49 (4), 625-659

- Gross T., MacCarthy B., Wildgoose N. (2018). Introduction to dynamics of manufacturing supply networks. *Chaos* 28(9):093111
- Gross, T., L Rudolf, SA Levin, U Dieckmann (2009). Generalized models reveal stabilizing factors in food webs. *Science* 325 (5941), 747-750
- Gross, T., W Ebenhöf, U Feudel (2004). Enrichment and foodchain stability: the impact of different forms of predator–prey interaction. *Journal of Theoretical Biology* 227 (3), 349-358
- Gupta V., Ivanov, D. (2020) Dual sourcing under supply disruption with risk-averse suppliers in the sharing economy. *International Journal of Production Research*, 58(1), 291-307.
- Harbour L. (2020). The coronavirus' impact on the global automotive supply chains. <https://www.forbes.com/sites/laurieharbour1/2020/03/13/the-coronavirus-impact-on-the-global-automotive-supply-chain/#185153c8444e>, [accessed on March 24, 2020]
- Haren, P., D. Simchi-Levi (2020). How Coronavirus Could Impact the Global Supply Chain by Mid-March. *Harvard 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
- Ho, W., T. Zheng, H. Yildiz & S. Talluri (2015) Supply chain risk management: a literature review. *International Journal of Production Research*, 53(16), 5031-5069.
- Holling, C.S. (1996). Engineering resilience versus ecological resilience. In: P.C. Schulze (Ed.) *Engineering within ecological constraints*. Washington D.C.: National Academy Press.
- Hosseini S., Ivanov D., Dolgui A. (2019a). Review of quantitative methods for supply chain resilience analysis. *Transportation Research: Part E*, 125, 285-307.
- 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*, 136, 101922, <https://doi.org/10.1016/j.tre.2020.101922>
- 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., Dolgui, A. (2019) Low-Certainty-Need (LCN) Supply Chains: A new perspective in managing disruption risks and resilience. *International Journal of Production Research*, 57(15-16), 5119-5136.
- Ivanov D., Dolgui A. (2020). 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., Dolgui, A., Sokolov, B. (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research*, 57(3), 829-846.
- Ivanov D., Kaeschel J., Sokolov B. (2009) Structure dynamics control-based framework for adaptive reconfiguration of collaborative enterprise networks. *International Journal of Manufacturing Technology and Management*, Vol. 17. No.1-2, pp.23-41.
- Ivanov D., Käschel, J., Arkhipov A., Sokolov B., Zschorn L. (2005): Quantitative Models of Collaborative Networks, In: *Collaborative Networks and Their Breeding Environments*, Proceedings of the IFIP Conference on virtual enterprises PRO-VE 2005, edited by L. Camarinho-Matos, Afsarmanesh, A. Ortiz, Springer, 2005, pp. 387-394.
- Ivanov D., Sokolov B., Dolgui A. (2014a). 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. (2014b). Optimal distribution (re)planning in a centralized multi-stage network under conditions of ripple effect and structure dynamics. *European Journal of Operational Research*, 237(2), 758–770.
- Ivanov, D. (2018). *Structural Dynamics and Resilience in Supply Chain Risk Management*. Springer, New York.

- Ivanov, D., Arkhipov, A., Sokolov, B. (2004): Intelligent Supply Chain Planning in Virtual Enterprises. In: *Virtual Enterprises and Collaborative Networks, Proceedings of the IFIP Conference on virtual enterprises PRO-VE 2004*, edited by L. Camarinho-Matos, Kluwer Academic Publishers, 2004, pp. 215-223.
- Ivanov, D., B. Sokolov (2013). Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis, and adaptation of performance under uncertainty, *European Journal of Operational Research*, 224(2), 313–323.
- Ivanov, D., B. Sokolov, J. Kaeschel (2010) A multi-structural framework for adaptive supply chain planning and operations with structure dynamics considerations, *European Journal of Operational Research*, 200, 409–420.
- Ivanov, D., Dolgui A., Sokolov B., Ivanova M. (2017). Literature review on disruption recovery in the supply chain. *International Journal of Production Research*, 55(20), 6158-6174.
- Ivanov, D., Sokolov B. (2012) The Inter-Disciplinary Modelling of Supply Chains in the Context of Collaborative Multi-Structural Cyber-Physical Networks, *Journal of Manufacturing Technology Management*, Vol. 23(8), 976-997.
- Kelly K., Marchese K. (2015). Supply chains and ISNs. Business ecosystems come of age. Deloitte University Press, pp. 55-65.
- Keogh, J. G. (2020). COVID-19. To ensure the supply of food and consumer goods, we must ‘Change the Rules of the Game’. www.foodincanada.com [accessed on March 20, 2020]
- Kim, Y., Chen, Y., Linderman, K. (2015). Supply network distribution and resilience: a network structural perspective. *Journal of Operations Management*, 33: 43-59.
- Liao, Y., Deschamps, Y., de Freitas, E., Loures R., & LFP Ramos (2017). Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. *International Journal of Production Research*, 55(12), 3609-3629.
- 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*, <https://doi.org/10.1016/j.ijpe.2019.107529>
- Linkov I., Kott, A. (2019). Fundamental concepts of cyber resilience: Introduction and overview. In: Kott A., Linkov I. (Eds.) *Cyber resilience of systems and networks*, Springer, Cham, pp. 1-25.
- Linton, T., Vakil B. (2020). Coronavirus Is Proving We Need More Resilient Supply Chains. *Harvard Business Review*, March 5, 2020, <https://hbr.org/2020/03/coronavirus-is-proving-that-we-need-more-resilient-supply-chains>, accessed on March 10, 2020
- Macdonald, J. R., Zobel, C. W., Melnyk, S. A., & Griffis, S. E. (2018). Supply chain risk and resilience: theory building through structured experiments and simulation. *International Journal of Production Research*, 56(12), 4337-4355.
- Mondal S. (2019). A new supply chain model and its synchronization behavior. *Chaos, Solitons and Fractals*, 123, 140-148.
- Nair A., Reed-Tsochas F. (2019). Revisiting the complex adaptive systems paradigm: Leading perspectives for researching operations and supply chain management issues. *J Oper Man*, 65(2), 80-92.
- Nair, A., J.M. Vidal (2011). Supply network topology and robustness against disruptions – An investigation using a multi-agent model, *International Journal of Production Research*, 49(5), 1391–1404.
- Niu B., Li J., Zhang J., Cheng HK., Tan Y. (2019). Strategic analysis of dual sourcing and dual channel with an unreliable alternative supplier. *Production and Operations Management*, 28(3), 570-587.
- 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.
- Olson, D.L., D. Wu, Y. Shanlin, J. H Lambert (2018). Complex product manufacturing in the intelligence-connected era. *International Journal of Production Research*, 57(21), 6702-6704.
- Panetto H., Iung B., Ivanov D., Weichhart G., Wang X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control*, 47, 200-213.
- Pathak S.D., Wu H., and Johnston D.A., “Toward a Structural View of Co-opetition in Supply Networks.” *Journal of Operations Management*, 2014, 32, 5, pp. 254-26

- Pavlov A., Ivanov D., Dolgui A., Sokolov B. (2018) Hybrid fuzzy-probabilistic approach to supply chain resilience assessment. *IEEE Transactions on Engineering Management*, 65(2), 303-315.
- Pavlov A., Ivanov D., Werner F., Dolgui A., Sokolov B. (2019a). 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
- Pavlov A., Ivanov D., Werner F., Dolgui A., Sokolov B. (2019b). Optimization of network redundancy and contingency planning in sustainable and resilient supply chain resource management under conditions of structural dynamics, *Annals of Operations Research*, <https://doi.org/10.1007/s10479-019-03182-6>
- Sarkis J., Talluri S., Gunasekaran A. (2007). A strategic model for agile virtual enterprise partner selection. *International Journal of Operations & Production Management*, 27(11); 1213-1234.
- Sawik T. (2017) A portfolio approach to supply chain disruption management. *International Journal of Production Research*, 55(7), 1970-1991.
- 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.
- Simchi-Levi D., H. Wang and Y. Wei (2018). Increasing Supply Chain Robustness through Process Flexibility and Inventory. *Production and Operations Management*, 27(8), 1476-1491.
- Spiegler V., Naim M. and Wikner J. (2012). A control engineering approach to the assessment of supply chain resilience. *International Journal of Production Research*, 50, 6162-6187.
- Surana, A., Kumara, S., Greaves, M., Raghavan, U.N. (2005) Supply-chain networks: a complex adaptive systems perspective. *International Journal of Production Research*, 43(20), 4235-4265.
- Tan WJ, Cai W. & A.N. Zhang (2020). Structural-aware simulation analysis of supply chain resilience. *International Journal of Production Research*, DOI: 10.1080/00207543.2019.1705421.
- Tang C.S., Veelenturf L.P. (2019). The strategic role of logistics in the industry 4.0 era. *Transportation Research Part E: Logistics and Transportation Review*, 129, 1-11.
- Wang, J., Muddada, R.R., Wang, H., Ding, J., Lin, Y., Liu, C. and Wenjun Zhang, (2014). Toward a Resilient Holistic Supply Chain NetworkSystem: Concept, Review and Future Direction. *IEEE Systems Journal*, 10(2), 410-421.
- Wang J., Dou R., Dou, Muddada, R.R., W. Zhang (2018). Management of a holistic supply chain network for proactive resilience: Theory and case study. *Computers and Industrial Engineering*, 125, 668-677.
- Yoon, J., S. Talluri, H. Yildiz, W Ho (2018). Models for Supplier Selection and Risk Mitigation: A Holistic Approach. *International Journal of Production Research*, 56(10), 3636-3661.
- Zhao K., Zuo Z., Blackhurst J.V. (2019). Modelling supply chain adaptation for disruptions: An empirically grounded complex adaptive systems approach. *Journal of Operations Management*, 65(2), 190-212.