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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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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 behaviours 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 conceptualisation 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), 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 globalised in structures, the SCs of many companies became specifically prone to coronavirus outbreaks (Ivanov 2020). The COVID-19 outbreak has not only immensely affected all areas of economy and society but also put the resilience of SCs to the test. Have the established SC resilience mechanisms (Blackhurst et al. 2005, Hosseini et al. 2019), e.g. risk mitigation inventories, subcontracting capacities, backup supply and transportation infrastructures, omnichannel distribution systems, flexible production technologies, and data-driven, real-time monitoring and visibility systems helped the companies to survive and recover through the pandemic times? 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 1000 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.

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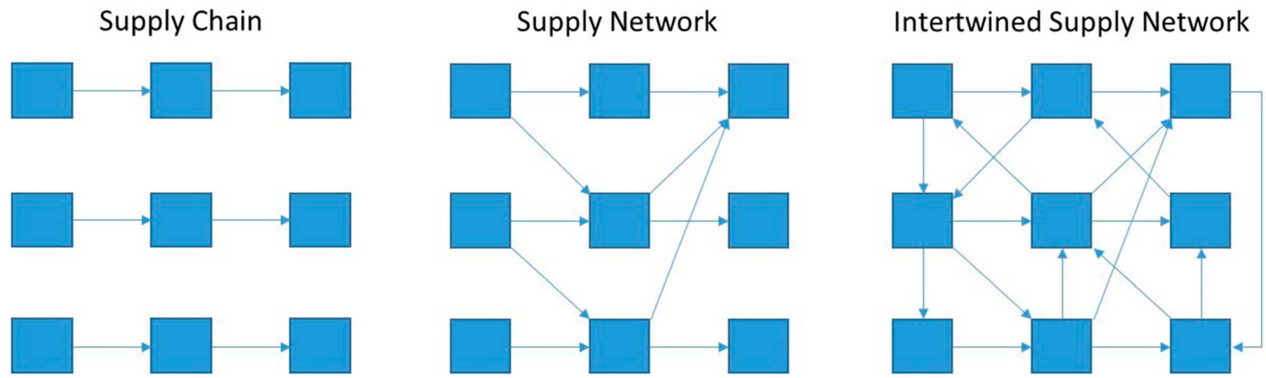

Figure 1. Linear supply chains, supply networks and intertwined supply networks.

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, Ivanov, and Rozhkov 2020; Hosseini, Ivanov, and Dolgui 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 modelling 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 et al. (2014) and Wang et al. (2018) 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 (Fraccascia, Giannoccaro, and Albino 2017; Choi, Taleizadeh, and Yue 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, Gunasekaran, and Papadopoulos 2019b). Considering the practical environments, Kelly and Marchese (2015) point to 'complex, dynamic, interconnected supply chains' highlighting to the role of information technology in synchronising 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 utilisation 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 characterised by structural dynamics (Ivanov, Sokolov, and Kaeschel 2010; Kelly and Marchese 2015). In contrast to linearly directed SCs or supply networks (cf. Figure 1) with static structures, the firms in the ISNs may exhibit multiple behaviours in buyer-supplier relations (i.e. behavioural dynamics) being buyers and suppliers in interconnected or even competing SC simultaneously.

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 electronic 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

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		+	+	+	+

are responsible to provide 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 behavioural 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 conceptualisation 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 summarise 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 behaviours 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 generalised 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, Ivanov, and Rozhkov (2020); Bier, Lange, and Glock (2019); DuHadway, Carnovale, and Hazen (2019); Hosseini, Ivanov, and Dolgui (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, Wang, and Wei 2018)
- Resilience – ability to withstand a disruption (or a series of disruptions) and recover the performance (Spiegler, Naim, and Wikner 2012; Hosseini, Ivanov, and Dolgui 2019).

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

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

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, Zuo, and Blackhurst 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 Bellamy 2014; Ivanov, Sokolov, and Dolgui 2014a, 2014b; Kim, Chen, and Linderman 2015; Brintrup, Wang, and Tiwari 2015; Sawik 2017; Macdonald et al. 2018; Yoon et al. 2018; Scheibe and Blackhurst 2018; Pavlov et al. 2018; Ojha et al. 2018; Giannoccaro, Nair, and Choi 2017; Ivanov 2018, 2019; Dolgui, Ivanov, and Sokolov 2018; Li et al. 2019; Pavlov et al. 2019b) recognised 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, Cai, and Zhang 2020). Ivanov and Dolgui (2019) emphasise 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, Xi, and Jing (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, Doyen, and Gabay 2001) *as a system ability to maintain itself and recover in the presence of disturbances over a long-term horizon*. In Table 2, we summarise the major differences between the resilience and viability.

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 behaviour-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 in 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 behaviours of the firms involved. For example, Zhao, Zuo, and Blackhurst (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, Arkhipov, and Sokolov 2004, 2005; Camarinha-Matos and Afsarmanesh 2005; Dekkers 2009; Ivanov, Kaeschel, and Sokolov 2009; Sarkis, Talluri, and Gunasekaran 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, Dooley, and Rungtusanatham 2001; Surana et al. 2005) and SC structural dynamics (Ivanov, Sokolov, and Kaeschel 2010).

Most recently, Fraccascia, Giannoccaro, and Albino (2017) point to the multiple, intersecting SCs in the industrial symbiosis which are characterised by using the waste of some SC processes as the inputs into the other SCs (Pathak, Wu, and Johnston 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, Dolgui, and Sokolov 2019; Panetto et al. 2019; Tang and Veelenturf 2019). Choi, Taleizadeh, and Yue (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 synchronised information technologies to coordinate value chains of different firms of ISN (Kelly and Marchese 2015).

2.3. ISN analysis inspired from ecology modelling

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, Ebenhöh, and Feudel 2004, 2009). Recent literature point to resemblance of the SCs to ecosystems (Byrne et al. 2018; Gross, MacCarthy, and Wildgoose 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 synchronisation in terms of balancing the demand and inventory levels (Anne, Chedjou, and Kyamakya 2009; Demirel et al. 2019; Mondal 2019).

Ecological perspective of the resilience has been developed by Holling (1996) 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 modelling 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 behaviours 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 optimisation tool for a particular decision-making setting. Our interpretation comprehensively combines major determinants of the ISNs, i.e. competition between suppliers, market demands, and behavioural dynamics.

3.1. Trophic chain

Trophic chains are a part of ecological modelling. Conceptually, trophic chains are used for modelling 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, Ebenhöh, and Feudel 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-López 2017).

It can be observed that the trophic chain exhibits some characteristics close to the SC. In literature, SCs are considered multi-stage systems in which dynamics are 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

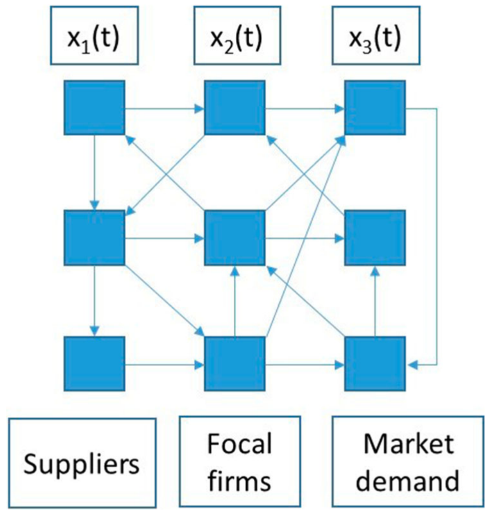

Figure 2. Intertwined supply network modelling.

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 (Figure 2).

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. Equations (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 behavioural strategies of suppliers, focal firms, and customers.

$$x_1{}'(\mathrm{t}) = x_1(t)(1 - u(t)x_1(t) - v(t)x_2(t)) := f_1(x(t), u(t), v(t), w(t)) \tag{1}$$

$$x_2{}'(\mathrm{t}) = x_2(t)(v(t)x_1(t) - w(t)x_3(t)) := f_2(x(t), u(t), v(t), w(t)) \tag{2}$$

$$x_3{}'(\mathrm{t}) = x_3(t)(w(t)x_2(t) := f_1(x(t), u(t), v(t), w(t)) \tag{3}$$

The dynamical game (1)–(3) considers the system evolution in time 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)

$$x'(t) \in F(x(t)) \tag{4}$$

under constraint (5)

$$x(t) \in K \tag{5}$$

remaining in a fixed closed set *K,* where

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

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

such that

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

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 behavioural 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, Doyen, and Gabay 2001) that considers *viability as a system ability to maintain itself and recover in the presence of disturbances over a long-term horizon*. In the SC settings, viability can be considered as an intersection of resilience, adaptability and sustainability. This calls for new understanding, new theories, and novel approaches concerning SC and ISN viability conceptualization, its antecedents, its drivers, and its economic and social performance implications.

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 digitalisation, 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 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 modelling 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 modelling 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 modelling (survival competition, agent modelling, 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 optimisation. 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 generalised flows. Such stylised 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 characterised by structural dynamics. Differently than linearly directed SCs with static structures, the firms in ISNs may exhibit multiple behaviours in buyer-supplier relations (i.e. behavioural 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 conceptualisation 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 viability is 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 generalised, '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 needs to be noted in 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 utilisation of *digital, data-driven technologies* to uncover their potentials to support the decision-making in cases of long-term, sever disruptions such as epidemic outbreaks. In particular, digital SC twins (Ivanov and Dolgui 2020) – i.e. the computerised SC models that represent the network state for any given moment in real time – can be further investigated in this direction. The importance of flexible and adaptable production and distribution systems (e.g. omnichannel, additive and digital manufacturing) along with reactive, real-time mapping of supply and demand will increase.

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