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#### **ORIGINAL RESEARCH**



# Collaborative emergency adaptation for ripple effect mitigation in intertwined supply networks

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## Abstract

For the first time, the ripple effect is examined in the setting of an intertwined supply network. Through simulations, we model the disruption propagation in supply chains having common suppliers. We explore conditions under which a collaborative coordination of re-purposed capacities and shared stocks can help mitigate the ripple effect and improve recovery performance. As a result, we conceptualize the notion of collaborative emergency adaptation contributing to development of "network-of networks" and viability perspective in supply chain resilience management. We illustrate our approach with anyLogistix simulations and deduce some generalized theoretical and managerial insights on how and when a collaborative emergency adaptation can be implemented and help improve supply chain resilience and viability.

**Keywords** Supply chain resilience · Ripple effect · Intertwined supply network · Collaboration · Adaptation · Viability · anyLogistix

# 1 Introduction

Disruptions at different echelons in supply chains can be localized without an associated cascading throughout a network, or propagate downstream and cause the ripple effect adversely impacting performance of individual firms and networks ((Ivanov et al., 2014a, b; Dolgui et al., 2018; Kinra et al., 2020; (Li et al., 2020b; Osadchiy et al., 2021; Iftikhar et al., 2022; Llaguno et al., 2022). According to Dolgui et al. (2020a), the ripple effect "refers to structural dynamics and describes a downstream propagation of the downscaling in demand fulfilment in the supply chain as a result of a severe disruption."

Bullwhip and ripple effects are two types of systemic risks and specific areas of supply chain resilience (Osadchiy et al., 2016; Scheibe & Blackhurst, 2018; Sawik, 2020, Ivanov and Dolgui, 2021, Li et al., 2021a, b; Katsaliaki et al., 2022; Hägele et al., 2023). While

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literature has mostly focused on the ripple effect in supply chains of particular firms, collaboration of different supply chain networks in the ripple effect settings remained underexplored. In particular, the intertwined supply network (ISN), which is an 'entirety of interconnected supply chains which, in their integrity secure the provision of society and markets with goods and services' (Ivanov & Dolgui, 2020) becomes an important concept where ripple effect examination is still missing. Moreover, moving the discussion toward ISNs has resulted in development of a new notion for supply chain disruption management, i.e., the viability, which integrates resilience and sustainability (Ivanov & Dolgui, 2020, Ivanov, 2021a, Sawik, 2023).

Viability is the "ability of a supply chain to maintain itself and survive in a changing environment through a redesign of structures and replanning of performance with long-term impacts" (Ivanov & Dolgui, 2020, Ivanov, 2022b). The viable supply chain model proposed by Ivanov (2022c) is a new approach to conceptualize intertwining of different supply chain designs echoed by Ivanov and Dolgui (2022a; Ivanov et al. (2023)) pointing to the importance of stress-testing the entire ecosystems, and not only firm's supply chains. Ruel et al. (2021) and Ivanov and Keskin (2023) stress the role of the ripple effect mitigation in building viable supply chains. Li et al. (2022a, b, c, d, e; MacCarthy et al., (2022)) elaborate on importance of supply chain preparedness and mapping pointing to the role of collaboration in adaptive emergency responses.

Managing disruptions in ISNs has several distinct problems and chances as compared to individual supply chains. Difficulties of the ripple effect control in the ISNs are triggered by ISN complexity, higher decentralization degree, and lower observability (Feizabadi et al., 2023). Chances are offered by a broader pool of resources available for adaptation, and structural network variety (Ivanov et al., 2023). Consider an example. During the COVID-19 pandemic, commercial and healthcare supply chains have been intertwined as an emergency response to shortages of medical equipment caused by the ripple effects of propagating disruptions in demand and supply (Choi, 2021). As shown in Ivanov (2021a), Ford's automotive supply chain intertwined with healthcare supply chains. Ford repurposed their production line to help healthcare sector to cope with a shortage of PPE (personal protection equipment) within two weeks. In collaboration with the hospital managers, face shields designs have been identified that could be built by a re-purposed Ford's supply chain. Material planning and logistics started planning inbound and outbound deliveries for the newly established product. Suppliers started delivering materials to production sites. On the same day, the first prototype was completed, and an initial prototype production run was established. Next day, new suppliers have been identified to resolve capacity problems with supply for some materials needed for the face shield production. The first 5,000 face shields arrived at the hospitals. Some problems needed to be operatively resolved. The supply of elastic bands was identified as not sufficient for full speed production. Alternative product designs have been validated, and new suppliers have been identified and contacted. Thus, in one week, Ford was able to go from idea to mass production. Other examples include Est'ee Lauder and Bacardi sanitizers and Gucci and Ralph Lauren masks and medical gowns. However, time delays, high coordination efforts, and long shortage periods occurred during these adaptations. For example, three-quarters of sanitizer manufacturers faced severe material shortage, including alcohol and packaging, after using full capacity to ramp up production (Paul & Chowdhury, 2021; Müller et al., 2022) provide empirical evidence of such a networking in companies that adopted ad hoc supply chain re-purposing. They examined adaptation processes with full range of related activities, i.e., to find new suppliers, to develop the products, to ramp-up production, and to distribute to new customers.

This cross-industry networking can be called a "network of networks" adaptation building on the concepts of physical internet (Pan et al., 2017), ISNs (Ivanov & Dolgui, 2020; Feizabadi et al., 2023), and supply chain commons (Chopra et al., 2021). Despite a considerable progress done in the ripple effect and ISN research separately, there is still a lack of understanding the ripple effect mechanisms in the ISNs. We define the following research questions (RQ) for our study:

RQ1: How does the timing of collaborative adaptation deployment impact the ripple effect and supply chain performance?

RQ2: When and how a collaborative coordination of re-purposed capacities and shared stocks in ISNs can help mitigate the ripple effect and improve recovery performance of supply chains?

Our contribution is twofold. First, we contribute to literature by examining the ripple effects in the ISN setting. We model the disruption propagation in supply chains, which are intertwined having common suppliers (contractual manufacturers). Through simulations, we explore the effects of collaborative disruption responses and conditions under which a collaborative allocation of shared/re-purposed capacities and stocks can help mitigate the ripple effect and improve recovery performance of supply chains. Second, we conceptualize the notion of collaborative emergency adaptation contributing to development of "network-of networks" perspective in supply chain resilience management. We illustrate our approach with anyLogistix simulations and deduce some generalized theoretical and managerial insights on how and when a collaborative emergency adaptation can help improve supply chain resilience.

The rest of this paper is organized as follows. Section 2 offers a literature review on the ripple effect, ISNs, and collaborative disruption management. In Sect. 3, the simulation model is described. Experimental results are presented and discussed in Sect. 4. Section 5 is devoted to theoretical and managerial insights. We conclude in Sect. 6 by summarizing major outcomes of this study and outlining some future research topics.

# 2 Literature review

We build on and contribute to three research streams, i.e., the ripple effect, ISNs, and collaborative disruption response. We organize our literature review accordingly.

#### 2.1 Ripple effect in supply chains

An increased interest in the ripple effect in supply chains has been observed at the beginning of the second decade of the 21st century (Liberatore et al., 2012; Ghadge et al., 2013; Mizgier et al., 2013; Swierczek, 2014; (Ivanov et al., 2014b; Zeng & Xiao, 2014; Garvey et al., 2015). The first definition of the ripple effect was coined by Ivanov et al. (2014a): "Ripple effect describes the impact of a disruption on supply chain performance and disruptionbased scope of changes in the supply chain structures and parameters ".

Research on the ripple effect has been considerably grown as documented in literature reviews by Dolgui et al. (2018), Hosseini et al. (2019), Ivanov and Dolgui (2021b), Dolgui

and Ivanov (2021), Shi et al. (2022) and Llaguno et al. (2022), as well the handbook of the ripple effect in supply chains ((Ivanov et al., 2019b). Most of the papers published before 2020 have studied propagation of a single disruption through some downstream echelons Han & Shin, 2016; Tang et al., 2016; (Ivanov, 2017, 2019; Levner & Ptuskin, 2018; Deng et al., 2019; Hosseini et al., 2020; Li & Zobel, 2020; Lei et al., 2021; (Hosseini & Ivanov, 2022b, Sindhvani et al., 2022, Yu et al., 2022). This body of literature developed multiple methods for mitigating the ripple effect through backup sourcing, capacity flexibility, and inventory optimization as well as for recovery in case of the ripple effect. One of the challenges in implementing these methods is the right balance of resilience and efficiency (Aldrighetti et al., 2023; Babai et al., 2022b, Ivanov, 2022a, Ivanov, 2022c; Li et al., 2022b; Alikhani et al., 2023; Babai et al., 2023). A specific topic in ripple effect research has been reverse logistics and closed-loop supply chains uncovering additional opportunities and challenges arising from reverse flows (Ivanov et al., 2017; Pavlov et al., 2019, Özçelik et al., 2021, Park et al., 2022).

Most recently, ripple effects driven by simultaneous disruptions in supply, demand, logistics, and capacities have been examined predominantly triggered by the COVID-19 pandemic (Ivanov, 2020, Singh et al., 2021; Ghadge et al., 2022; Hosseini & Ivanov, 2022a; Brusset et al., 2022; Delasay et al., 2022; Ramani et al., 2022). These studies indicated differences in managing the ripple effect under singular disruptive events and long-term crises. They concluded that ripple effect control under crisis is complicated by simultaneous disruptions in supply, demand, and capacities, recovery in the presence of disruptions, and unpredictable scaling of disruptions.

Methods used for ripple effect analysis include discrete event simulation (Schmitt et al., 2017, Ivanov, 2021b, Rozhkov et al., 2022; Ivanov, 2022d; Timperio et al., 2022), system dynamics simulation (Ghadge et al., 2022), agent-based simulation (Li et al., 2021a, b), Bayesian networks (Ojha et al., 2018; Hosseini et al., 2020; Liu et al., 2021), optimal control (Ivanov et al., 2014a; Brusset et al., 2022), fuzzy logic (Pavlov et al., 2022), network theory (Li et al., 2020a, b), and optimization (Gholami-Zanjani et al., 2021; Liu et al., 2022; Sawik, 2022).

#### 2.2 ISNs and network-of networks

Ivanov and Dolgui (2020) framed the notion of Intertwined Supply Network (ISN) concept considering intersecting supply chains in different industries and ecosystems. They used a game-theoretical ecological model to show that intertwining as an adaptation strategy can help ensure viability during a large-scale crisis. Wang and Yao (2023) proposed an optimization model for ISN design under disruptions. Feizabadi et al. (2023) studied the jury-rigging perspective to examine ISN resilience. A similar approach has been proposed by Chopra et al. (2021) based on using multi-level commons which is "a set of pooled resources for the flow of information, product, or funds". They note that "companies that used multiple channels to improve efficiency when facing day-to-day demand-and-supply variations found that the structure also offered resilience without additional cost when COVID struck".

Ballot et al. (2014) developed a Physical Internet notion, which combines principles and technologies to manage supply chains from the perspective of networking logistics networks. Pan et al. (2017) has developed this idea further applying principles of data networks in digital internet for physical networks. Niu et al. (2019) note that Apple and Samsung

play roles of both suppliers and competing firms in two different intersecting supply chains. They developed a game-theoretic study to analyse component sourcing quantity allocation in such settings. Choi et al. (2020), MacCarthy and Ivanov (2022), Ivanov (2022b), Ivanov et al. (2022), and Zhang et al. (2022) point to collaborative and intertwined business ecosystems forming cloud and digital supply chains and platforms responsible for securing society's needs in line with natural, economic, and governance interests.

ISNs add flexibility required for adaptation. Flexibility has been proven to be one of the central capabilities to adapt and recovery after disruptions (Shekarian et al., 2020). The principal ideas of the viable supply chain and ISN are "adaptable structural supply chain designs for situational supply-demand allocations and, most importantly, the establishment and control of adaptive mechanisms for transitions between the structural designs" (Ivanov, 2022b).

#### 2.3 Collaborative disruption response

Collaboration has been indicated to be an important capability to manage disruptions (Dolgui & Proth, 2010; Scholten & Schilder, 2015; Hedenstierna et al., 2019, Nguyen et al., 2019, Duong & Chong, 2020; Li et al., 2022c). In reality, supply chains of different sectors and ecosystems are not entirely separated from each other. They usually intersect at several points sharing common suppliers and warehouses (Niu et al., 2019; Zhao et al., 2019; Azadegan & Dooley, 2021; (Li et al., 2021b). For example, automotive industry suppliers are at the same time producers of valves for ventilators leading to intertwining of supply chains in automotive and healthcare ecosystems (Ivanov, 2021a). Hedenstierna et al. (2019) elaborate on the economies of collaboration stressing the responsiveness of build-to-order operations. Gupta et al. (2021) examined the impact of disruption timing on decisions to substitute a missing product by another with similar properties produced by a backup supplier. Li et al. (2022a, e, (2023) elaborated on the recovery strategies in the presence of price dynamics and uncertain disruption duration. Müller et al. (2022) described ad-hoc intertwining of commercial and healthcare supply chains as a response to COVID-19 pandemic and medical equipment shortages. They point to the importance of coordination and timing in collaborative emergency response. Shi et al. (2022) provide a survey of recent literature dealing with the ripple effect from a collaboration perspective.

Summarizing our literature review, it can be concluded that literature is rich on the ripple effect in supply chains, understanding its mechanisms and proposing mitigation and recovery strategy. Driven by the pandemic and other instabilities faced through global geopolitical conflicts, shortages of critical components (e.g., semiconductors), and economy and energy crisis, the focus of analysis has been shifted toward ISNs and their viability. However, to the best of our knowledge, none of the previously published research has examined the ripple effect in the ISNs – a distinct and substantial contribution made by our study. To close this research gap, we explore the effects of collaborative disruption responses on the ripple effect in ISNs.

# 3 Simulation model

Ripple effect analysis in combination with the ISN context results in a highly dynamic system with uncertainties. Following (Dolgui et al., 2018; Llaguno et al., 2022; Ivanov et al., 2023), simulation is best-suited method for such analysis. Our discrete-event simulation model is developed in anyLogistix software. In the ISN considered for modelling, there are three supply chains of firms representing different industries (Fig. 1).

Firms produce three different products serving three non-connected markets. However, all three producers of final products P1-P3 use a common material M1, which is delivered by a common supplier. Moreover, some technological intertwining is possible. In particular, firm 1 in industry 1 produces a material M12, which can be used as a substitute in industry 2. Similarly, firm 2 can produce a substitute M23 for industry 3, and firm 3 can supply industry 1 with a substitute material M31. Firms also collaborate on inventory management and can share with each other inventory of M1 in case of need.

The following assumptions have been done for setting up the simulation model:

- 1) Demand is normalized to 1 unit, and each customer places order of one unit of demand every three days at firms 1–3.
- 2) No back-ordering is possible so if a customer order is not fulfilled on-time, the order is lost and cannot be delivered later.
- An order is considered to be fulfilled on time if it is delivered within five days after placing an order at factory (so called expected lead time).
- 4) Order-up-to-level inventory control system is used in all the supply chains, whereas the re-order point equals two units, and the target inventory equals 4 units. For warming-up the simulation, we allow for four units of initial stock at all echelons of supply chains.



Fig. 1 ISN for simulation modeling

- 5) Production of substitute material for another industry does not affect production utilization and capacity at a site; in other words, no capacity constraints are considered.
- 6) Bill-of-materials of all three products P1-Pcontains material M1
- Lead time between supplier and factories is two days, between factories and customers - four days, and between factories- four days.
- 8) For analysis, a period of *four* months is used from January 6, 2023 to May 5, 2023.
- 9) There is a disruption event at supplier starting at March 5, 2023 with a recovery period of 60 days during which supplier 1 is unavailable.
- 10) For ripple effect analysis, the demand fulfillment indicator is used. It counts the number of products delivered at the customer on time.

# 4 Experimental results

We structure simulation results in three parts as follows:

- a baseline scenario without any collaboration between supply chains.
- impact of collaboration on ripple effect mitigation.
- impact of adaptation speed of collaborative emergency response on ripple effect mitigation.

#### 4.1 Baseline scenario

In this scenario, there is a supplier disruption, and no collaboration between supply chains is considered as a response reaction (Fig. 2).

First, we show the results of a disruption-free performance, and then the results in the disruption case (Figs. 3 and 4, respectively).

When comparing Figs. 3 and 4, it can be observed that the supplier disruption causes the ripple effect indicated by a significant reduction of the fulfilled demand (a reduction from 114 to 78 units). While the existing inventory allows covering demand at the beginning of the disruption period, a backlog begins growing 12 days after the supplier disruption. We note that the left-hand side inventory diagrams in Figs. 3 and 4 illustrate available inventory and backlog dynamics for material M1 while the right-hand side inventory diagrams in Figs. 3 and 4 illustrate available inventory dynamics for final products P1-P3 (since no backlog is allowed in the model, there is no backlog for final products).

#### 4.2 Collaboration impact on ripple effect mitigation

In this part of experiments, we examine the ISN collaboration impact on the ripple effect. In particular, we now allow for:

- inventory sharing among manufacturers,
- capacity re-purposing and usage of substitute materials (through usage of backup technology plans).



Fig. 2 Baseline simulation model



Fig. 3 Supply chain performance in a baseline scenario

After a disruption at the supplier, the factories first share inventories of M1, then increase capacity to produce a substitute product, and finally utilize capacity re-purposing. In particular, the adaptation algorithm first check inventory availability for M1 and re-allocates it to the demand points. If no M1 inventory is available, the algorithm increases production capacity. As the last measure, capacity is re-purposed. The results are shown in Fig. 5.

It can be observed in Fig. 5 that collaboration efforts allow mitigating the ripple effect and even improve the baseline performance to some extent. While results shown in Fig. 5 assume an immediate re-purposing of supply chains, even in a very well-coordinated ISN, some reaction delays can happen. As such, we now investigate the impact of adaptation



Fig. 4 Supply chain performance with a supplier disruption and no collaboration



Fig. 5 Supply chain performance with a supplier disruption and ISN collaboration

time (i.e., TTA – time-to-adapt (Ivanov, 2021a)). Figures 6 and 7 depict simulation results of sensitivity analysis regarding TTA.

When analysing results shown in Figs. 5–7, it can be observed that TTA has an immediate impact on ripple effect mitigation through collaboration efforts. While TTA of two weeks is enough to mitigate the ripple effect, a four-week TTA results in some ripple effect reflected in the reduction of fulfilled demand. However, the ripple effect is much less as compared to non-collaborative scenario (Fig. 3).



Fig. 6 Supply chain performance with a supplier disruption, ISN collaboration, and TTA=2 weeks



Fig. 7 Supply chain performance with a supplier disruption, ISN collaboration, and TTA=4 weeks

# 5 Theoretical and managerial insights

The anyLogistix model proposed in the paper can help design and investigate adaptation scenarios for ripple effect mitigation in the ISN. It illustrates and generalizes the problem of a collaborative emergency adaptation considering multiple intersecting supply chains. The model allows not only to promptly propose an adaptation plan and its deployment in an emergency case but also, and most importantly, to generalize and illustrate the requirements on data and coordination mechanism during a collaborative emergency response.

Our results indicate that collaborative emergency adaptation can help mitigate the ripple effect in ISNs. The results allows us to generalize the *notion of collaborative emergency response* as a composition of a digital supply chain, structural and process preparedness, and collaborative response (Table 1).

ISN Capability	ISN Implementation
Digital supply chain	<ul> <li>Visibility about inventory and capacity</li> <li>Collaborative supplier, manufacturer and logistics portals (coordination)</li> <li>Digital twin (mapping)</li> </ul>
Structural and pro- cess preparedness	<ul> <li>Backup technology plans and capacity flexibility (for re-purposing / use of substitute materials)</li> <li>Shared structural elements (e.g., factories and warehouses)</li> </ul>
Collaborative response	<ul> <li>Collaborative adaptation deployment (simulation model and organizational rules)</li> <li>Emergency-driven capacity re-purposing and stock re-allocation (if shortage happens in one industry, supply chains of other industries can help to survive through the recovery time)</li> </ul>

Table 1 Generalization of the collaborative emergency response capabilities

The principles of collaborative emergency response implementation in practice shown in Table 1 can be described as follows. We have shown that the proposed approach has benefits to improve responsiveness of a disruption response through cross-industry collaboration. Concrete implementation actions are preparedness, coordination, emergency capacity re-purposing and stock re-allocation, and collaborative recovery deployment. First, we observed that a collaborative adaptation helps attain a timely disruption response in a cross-industry setting utilizing synergies in the ISNs (e.g., inventory sharing, capacity repurposing, and usage of substitute materials). The second observation is that adaptation success depends on the timing of response deployment. Some preparedness in the form of backup technology plans, visibility, and digital collaboration platforms helps to improve responsiveness of the adaptation deployment. Third, our analysis notes the importance of visibility of relevant SC data and timely pre-allocation / re-purposing of the ISN structures, processes, and products based on coordination between different supply chains.

# 6 Conclusions

Ripple effect became one of the major stressors to supply chain resilience. While considerable progress in ripple effect research with the focus on firm's supply chains can be observed, the literature is still silent about the ripple effect in ISNs. ISNs span supply networks of different industries and ecosystems that have common suppliers, logistics capacities, and warehouses whereas companies can play the role of buyers in one network, and the role of suppliers – in another one.

In this paper, for the first time, the ripple effect was examined in the ISN setting. Through simulations, we modelled the disruption propagation in supply chains having common suppliers (contractual manufacturers) and warehouses. We illustrated our approach with anyLogistix simulations and deduce some generalized theoretical and managerial insights on how and when a collaborative emergency adaptation can help improve supply chain resilience. We explored conditions under which a collaborative coordination of shared/re-purposed capacities and stocks can help mitigate the ripple effect and improve recovery performance of supply chains. As a result, we conceptualized the notion of collaborative emergency adaptation as a composition of a digital supply chain, structural and process preparedness,

and collaborative response. Using the model, we demonstrated a superiority of the proposed collaborative response when compared to non-collaborative recovery actions of individual supply chains. With these results, our study contributes to development of "network-of networks" and viability perspective in supply chain resilience management.

Limitations of our study belong to contextual nature of insights deduced from simulations rather than from analytical derivations. Besides, a detailed analysis of contributions of individual ISN capabilities (i.e., visibility, re-purposing and inventory sharing) to performance improvement remained outside of this study.

In future, some extensions of our study can be considered. First, ISN adaptation is frequently based on resources sharing and pooling. For example, inventory sharing is indeed a way to mitigate the ripple effects, but since the entire ISN system includes multiple different industries (and their supply chains), the relationships between supply chains are also relatively complex. As such, consideration of competition and cooperation between different supply chains can lead to interesting conclusions and game-theoretical models. Second, new digital twin-based and artificial intelligence-based methods can be explored to detect intersections of supply chains and shared resources (Ivanov et al., 2019a; Burgos & Ivanov, 2021, Ivanov & Dolgui, 2021a, Dubey et al., 2021a, Dubey 2021b, Kosasih & Brintrup, 2021, Kegenbenkov and Jackson 2021, Rolf et al., 2022).

Importance of ISN-based analysis will grow in next years in light of the digital supply chains, platforms, shortage economy, and Industry 5.0 MacCarthy & Ivanov, 2022; (Ivanov & Dolgui, 2022b, Ivanov and Keskin, 2023, Li et al., 2022d). In these settings, novel settings are offered for research, e.g., contracting in the ISN, stress-tests of intertwined network design, inventory and product control policies with consideration of intertwining effects, dual/backup sourcing policies with material substitution, to name a few. The ISN context allows producing novel and substantial contributions and we expect more developments in this area in next years (Ivanov, 2023, Brusset et al., 2023).

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#### Declarations

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