Decomposing Supply Chain Complexity: A Multilayer Network Perspective

Phu Nguyen [*] **Dmitry Ivanov** [*]

[*] *Berlin School of Economics and Law, Badensche Str. 50, 10825 Berlin, Germany (e-mail: phu.nguyen@hwr-berlin.de, dmitry.ivanov@hwr-berlin.de)*

Abstract:
Contemporary supply chains have evolved into highly complex systems characterized by multifaceted interactions between entities within and across firms. The linear and isolated view of the supply chain often fails to capture the operational inter-dependencies when addressing a supply chain problem. Our study proposes to view supply chains through the lens of a multilayer network perspective. First, we propose the principal layer, the so-called direct supplier-buyer network, encompassing the focal firm, its immediate supplier, and buying firms. Second, we extend to a deep-tier supply network layer, capturing firms with indirect relationships. Firms do not typically have good visibility for deep-tier suppliers and sometimes suffer a significant impact of the ripple effect. Third, to facilitate more effective management of material dependencies, we introduce the product-integrated network mapping the products and required materials. Finally, we propose a process-integrated network to represent how materials are transformed into final products. The four-layer network framework, therefore, offers a unified, integrated, and interoperable approach to better manage supply chain operations. We also present a case study from a leading European manufacturing firm and highlight how the presentation of a four-layer supply network supports digital transformation and enhances supply chain resilience.f

Keywords: Digital supply chain, supply chain network, supply chain resilience, supply chain modeling, operational interdependence.

1. INTRODUCTION

Supply chains have advanced into complex and interwoven networks (Harland, 2021). As firms coordinate procurement, production, and demand fulfillment across organizational boundaries, the silo approach often fails to align decision-making at different levels, timing, and time horizons. Recent disruptions — such as the COVID-19 pandemic and geopolitical conflicts — have further exposed the fragility of isolated systems (Habibi et al., 2025; Zhang et al., 2024). The propagation of disruptions through deep-tier suppliers, known as the ripple effect, has triggered cascading material shortages and halted production in various sectors (Dolgui et al., 2018). This highlights the existence of interconnected effects across the macro- (network-wide), meso- (organizational), and micro- (product-level and process-level) layers of the supply chain uncertainty (Flynn et al., 2016).

A growing body of research emphasizes the relevance of complex adaptive systems (CAS) thinking in supply network analysis, recognizing that supply chains behave like interconnected ecosystems (Choi et al., 2001). Network-based views offer a powerful lens to understand the structural complexities by revealing supply chain and operations configurations (Bier et al., 2020; Choi and Hong, 2002; Kim et al., 2015). Ivanov et al. (2010) further highlights that supply chains can take on various network structures—based on product architecture, organizational layers, and geographical distribution—each with unique implications for supply chain management under both normal and crisis conditions.

Building on the above insights, we aim to explore the application of network science in supply chain management as the following research question articulates:

How can a multilayer network framework improve the interoperability and resilience of supply chain systems?

To address the research question, we propose a multilayer network framework that integrates four interrelated layers (see Figure 1), each representing a distinct dimension of supply chain structure:

(1) Deep-tier supply network — capturing indirect upstream and downstream dependencies.
(2) Direct supplier-buyer network — representing first-tier relationships with the focal firm.
(3) Product-integrated network — connecting products and required components in the focal firm.
(4) Process-integrated network — mapping the internal transformation processes within the focal firm, linking input materials to intermediate steps and final products.

By combining the four layers, we offer an interoperable representation of supply chain operations that supports both strategic, tactical, and operational coordination. The proposed framework holds significant potential for en-

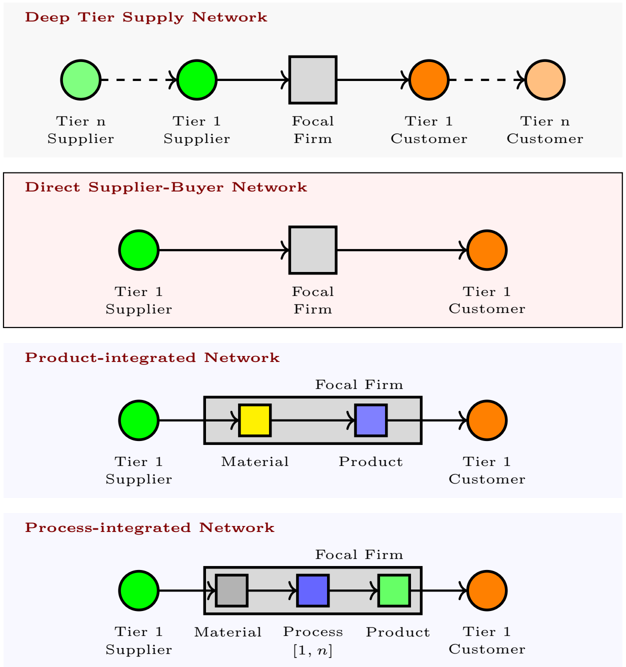

Fig. 1. Illustration of a four-layer supply chain network

abling a digital supply chain twin (Ivanov, 2023, 2024a) and empowers us to proliferate the rich theory of network science in supply chain and operations management. To demonstrate the practical applications of the proposed approach, we employ a real-world case in the leading European manufacturing firm whose supply chain is deeply tiered, tightly regulated, and disruption-sensitive. We also explain how the multilayer network is constructed and is applied to strengthen firm resilience in the case study.

Our paper makes three contributions. First, we introduce a novel multilayer network framework for supply chain modeling that captures structural, product-integrated, and process-integrated dimensions. Second, we propose how to operationalize the four-layer framework to support decision-making at multiple granularity levels and at the system-wide level. Third, we validate our approach through an empirical case study, highlighting its potential to address both academic and industrial challenges.

The remainder of this paper is organized as follows: Part 2 provides background on the study, highlighting the need for an integrated approach. Part 3 details the modeling methods to construct a four-layer network. In Part 4, we present our case study. Finally, Part 5 concludes our study.

2. BACKGROUND

2.1 Downsides of isolated views

Firms have managed their supply chain and operations through siloed approaches (Harland, 2021). In traditional organizational structures, procurement, production, and logistics are often treated as independent departments, each optimized locally with little integration across functions or organizational entities. Even within a single department, misalignments can occur between planning horizons, such as long-term capacity planning and short-term materials requirements planning. While significant efforts have been made to minimize discrepancies—such as collaborative planning, supply-demand alignment processes, and integrated business planning—these mechanisms often address the consequences of fragmentation, not the root causes. Recent events have starkly exposed the vulnerabilities of the isolated approach (Harland, 2021). The COVID-19 pandemic, semiconductor shortages, and geopolitical disruptions have shown that effective response to supply chain shocks requires rapid, coordinated action across multiple functions and organizations under significant time constraints (Ivanov, 2024a,c).

Disruption propagation or the ripple effect highlighted the risks of managing supply networks with a narrow focus on first-tier relationships (Dolgui et al., 2018). Supply chain uncertainty exists simultaneously at the micro- (product/process), meso- (organizational), and macro- (network) levels (Flynn et al., 2016). In particular, there is a statistically significant relationship between macro-level and micro-level uncertainty, indicating cross-level interactions of uncertainties (Flynn et al., 2016).

Similarly, disruption overlay theory suggests examining the supply chain beyond isolated perspectives. Disruption overlay occurs when the ripple effect meets the bullwhip effect (Ivanov, 2024b). While the bullwhip effect describes demand amplification and response inefficiencies at the micro- and meso-levels, the ripple effect captures the cascading failures typical of macro-level disruptions. The global chip shortage is an example of aggravated disruption overlay and provides evidence of the interfaces among supply chain layers (Nguyen et al., 2023). Unfortunately, most decision-support models in academia and practice operate within a single layer, failing to reflect interconnected dynamics and their compound impacts.

Another challenge arises in aligning decisions across time horizons. Strategic decisions—such as network design or sourcing policies— are typically made on a yearly basis or even a one-time basis. In contrast, tactical decisions (e.g., inventory replenishment or transportation modes) are reviewed weekly or monthly, while operational decisions (e.g., order release or shift scheduling) change daily or even hourly. Without a unifying framework, decisions made at different levels of time granularity may conflict. The temporal misalignment exacerbates fragility and reduces the adaptability of supply chains in the face of volatile environments.

In the broader scope of a supply chain network, optimizing at the single organization level leads to inefficiencies for the whole system (Majumder and Srinivasan, 2008). Similarly, isolated or linear decision models systematically underestimate the severity of disruption propagation (Zhang et al., 2024). Without inter-layer coordination, firms significantly understate their exposure to supply chain risks, reducing the overall resilience.

2.2 Toward integrated views

In response to the limitations of siloed approaches, a growing body of research has adopted integrated and network-based perspectives (Bier et al., 2020). Besides, CAS has emerged to capture the dynamic and interdependent nature of modern supply networks (Choi et al., 2001). Rather than perceiving supply chains as linear constructs, supply chains can be viewed through the lens of CAS as systems composed of interconnected actors, flows, and emergent mechanisms (Choi et al., 2001). A foundational concept in this stream is the representation of supply chains as networks, where nodes represent firms, products, or processes, and edges encode transactional, structural, or informational dependencies (Bier et al., 2020; Ivanov et al., 2010). CAS framework enables researchers to analyze emergent behaviors under disruption, assess structural vulnerabilities, and simulate propagation effects (Basole and Bellamy, 2014; Kim et al., 2015; Namdar et al., 2024; Zhao et al., 2019).

Integrated approaches have focused on using interdependent supply chain networks, which account for multiple interactions, such as physical and information flows, within and across firms (Zhang et al., 2024). Habibi et al. (2025) examines how disruptions propagate across multitier networks and the extent to which redundancy, tier depth, and coupling intensity affect network resilience. The findings underscore the importance of modeling supply chains beyond first-tier relationships and call for improved visibility into deep-tier supplier structures.

Other researchers investigate supply chain network at the micro-level (e.g., product level) (Olivares Aguila and ElMaraghy, 2018). For instance, bill-of-materials (BoM) networks are used to trace component dependencies and material flows within a focal firm. The supply chain stress-test model also connected the deep-tier and BoM networks (Simchi-Levi et al., 2015). Similarly, process-integrated models, typically modeled by discrete-event simulation, help firms evaluate production bottlenecks and resilience at the firm level. However, micro-level models are often disconnected from supplier structures and fail to reflect inter-organizational dynamics.

In summary, although significant progress has been made in capturing supply chain complexity through network-based methods, existing models remain limited in integrating multiple dimensions of the supply chain simultaneously. Most approaches focus on one or two levels but do not unify them into an interoperable framework. To bridge the explained gap, we propose a multilayer network framework integrating four dimensions of supply chain structure: the deep-tier supplier network, the direct supplier-buyer network, the product-integrated network, and the process-integrated network. The framework supports comprehensive visibility and improves alignment across entities. Besides, using the multilayer network allows us to proliferate the rich theories of network science.

3. METHOD

A multilayer network is a suitable approach as it could capture the heterogeneous and interdependent nature of the supply chain and allow us to investigate how decisions propagate across diverse levels. The proposed multilayer network is a set of four graphs $\mathcal{M} = \{G_1, G_2, G_3, G_4\}$, where each graph $G_i = (V_i, E_i, W_i)$ represents a distinct structural layer of any supply chain system. In this section, we discuss how to model each layer and establish inter-layer connections.

3.1 Layer 1: Deep-tier supplier network

The first layer captures the high level of firm dependencies and is arguably a typical approach to employing network science to address supply chain problems. We define the deep-tier supplier network as a directed graph $G_1 = (V_1, E_1, W_1)$, where:

- V_1 is the set of the focal firm and all nodes with transactions with the focal firm.
- E_1 denotes the relationships between firms.
- W_1 assigns transaction volumes or amounts.

Modeling this layer may require commercial data such as FactSet, Mergent, and Bloomberg (Culot et al., 2023). Researchers also use data scraping to collect data from a limited number of focal firms. Although the layer is very helpful in identifying nexus materials and potential connections to reduce the risk of disruption, the accuracy level remains low due to data completeness.

3.2 Layer 2: Direct supplier-buyer network

The direct-tier network is modeled as $G_2 = (V_2, E_2, W_2)$, where:

- $V_2 \subseteq V_1$ includes the focal firm and its direct (first-tier) suppliers and customers
- $E_2 \subseteq E_1$ represents transactional relationships.
- W_2 encodes purchasing quantities or amount.

By definition, G_2 is a subgraph of G_1. Firms typically understand their direct connections well. The second layer is, therefore, common to support decision-making at the strategic and tactical levels and requires a higher level of accurate presentation. Besides, data to construct Layer 2 is typically easy to acquire.

3.3 Layer 3: Product-integrated network

We define a multipartite graph $G_3 = (V_3, E_3, W_3)$, where:

- V_3 consists of final products and associated materials, suppliers responsible for providing materials, and customers demanding the final products.
- E_3 denotes material requirement relationships.
- W_3 represents quantities and consumption rates documented in BoMs.

While Layers 1 and 2 are homogeneous networks, the product-integrated network layer is heterogeneous. The core of this layer is BoMs. We could use Layer 3 to identify nexus materials and nexus direct suppliers.

3.4 Layer 4: Process-integrated network

The internal operations of the focal firm are modeled as $G_4 = (V_4, E_4, W_4)$, where:

- V_4 denotes manufacturing workstations or operational stages.
- E_4 captures manufacturing flows.
- W_4 quantifies the material flows.

This layer allows the modeling of production capacity constraints and identifies bottlenecks. In other words, it has the highest granularity and requires a high level of accuracy to be useful.

3.5 Inter-layer connections

We need to define connections of relevant elements to establish connections across layers. For example, direct suppliers are linked to partner nodes in the broader deep-tier network. Suppliers are connected to the components they provide, while each component is further connected to the internal processes responsible for its transformation. The bilateral or non-directed links enable a seamless transition from high-level abstractions to detailed representations of the supply chain. The inter-layer connection, therefore, allows us to model how a supply chain disruption impacts different levels of a supply chain and supports better coordination and decision-making across different functions.

4. CASE STUDY

To demonstrate the proposed multilayer supply chain network framework's applicability, we apply it to a real-world case of a key player in the European manufacturing industry, who wishes to remain anonymous in our study. The focal firm's supply network is characterized by complex product structures and highly regulated production processes, making it a suitable testbed for modeling interdependencies across multiple supply chain layers.

4.1 Layer 1: Deep-tier supply network

The deep-tier network captures the indirect suppliers that may include the nexus suppliers. Due to long lead times and low visibility, disruptions at this level can propagate downstream with significant consequences. The structure of the deep-tier network is described in Table 1. Data up to tier-2 suppliers and tier-1 customers was collected using web scraping. As it is in the early stage of the project, the first layer offers users a better understanding of the focal firm's deep-tier supply network.

Table 1. Network statistics of Layer 1

	Customer	Tier-1 Supplier	Tier-2 Supplier
Nodes count	130	251	1479
Min in-degree	1	0	0
Max in-degree	1	262	1
Mean in-degree	1	9.17	0.01
Median in-degree	1	0	0
Min out-degree	0	1	1
Max out-degree	0	13	8
Mean out-degree	0	2.84	1.24
Median out-degree	0	2	1

4.2 Layer 2: Direct supplier-buyer network

The direct supplier-buyer is the focal network of the firm in our case study. First, the focal firm has good quality data to construct this layer, even with significant inter-plant processes. The relationships are managed through part development and qualification processes, as well as the procurement process. In this study, we focus on a single major body part of the product. The direct supplier-buyer network includes 82 direct suppliers and one customer. Additionally, we can also extract data from Layer 1 to enrich Layer 2.

4.3 Layer 3: Product-integrated network

The product-integrated network models the structure of the focal product, which is assembled from multiple standard and specialized components. Nodes in the interfaces between Tier-1 suppliers and a customer represent materials or components, while edges reflect BoM relationships. Layer 3 is particularly helpful in tracing material dependencies and understanding how disruptions affect specific products. The real-world data of the focal product is illustrated in Figure 2.

4.4 Layer 4: Process-integrated network

The process-integrated network captures internal operations within the focal firm's manufacturing facilities. It maps the transformation of components across workstations, from materials sourced from global suppliers to final product assembly. This layer supports analysis of production bottlenecks and process-level resilience. A representation of Layer 4 network is provided in Figure 3.

Our project's current result is the complete modeling of the four-layer supply chain network for the focal firm. The next phase of our study focuses on connecting the individual layers and refining the use cases to better demonstrate the framework's applicability. We also observe the significant potential of applying the proposed framework in supply chain digitalization (Ivanov, 2023, 2024a).

5. CONCLUSION

Our paper introduces a multilayer network framework for modeling supply chains as interconnected systems spanning organizational, product, and operational dimensions. We propose four layers — deep-tier supply network, direct supplier-buyer network, product-integrated network, and process-integrated network — and formalize each as a graph with distinct network structures and interdependencies. The framework provides a comprehensive view of inter-organizational dependencies and internal operational flows, bridging strategic, tactical, and operational perspectives.

We validate the framework through a case study in the industrial sector, demonstrating its potential to enhance supply chain resilience and support digital transformation initiatives. Our initial implementation focuses on constructing four graphs for a four-layer supply chain using real-world data from the focal firm and focal product. The two micro-level layers allow us to capture the internal complexity of manufacturing workflows and material flows, laying the foundation for multilayer resilience analysis. In the next phase of the project, we will develop the interfaces among network layers. We also aim to integrate the multilayer network into a digital supply chain twin to offer decision-makers an integrated tool for supply chain resilience, scenario testing, and system-wide optimization.

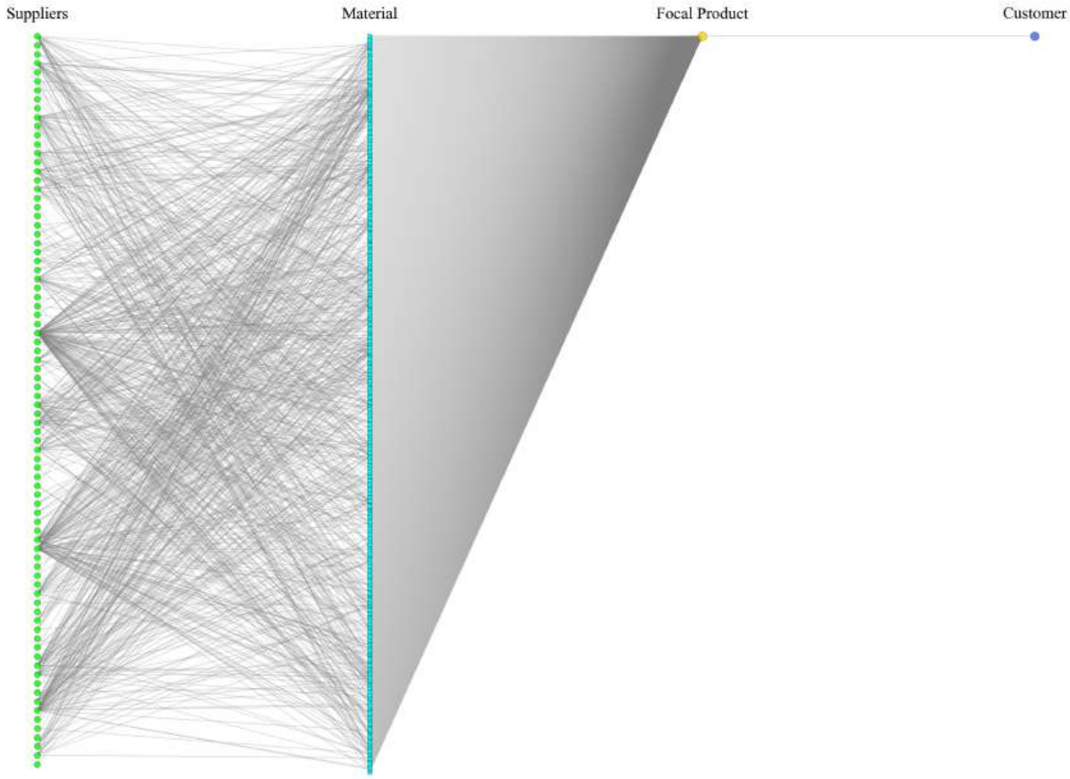

Fig. 2. Product-integrated network of the focal product

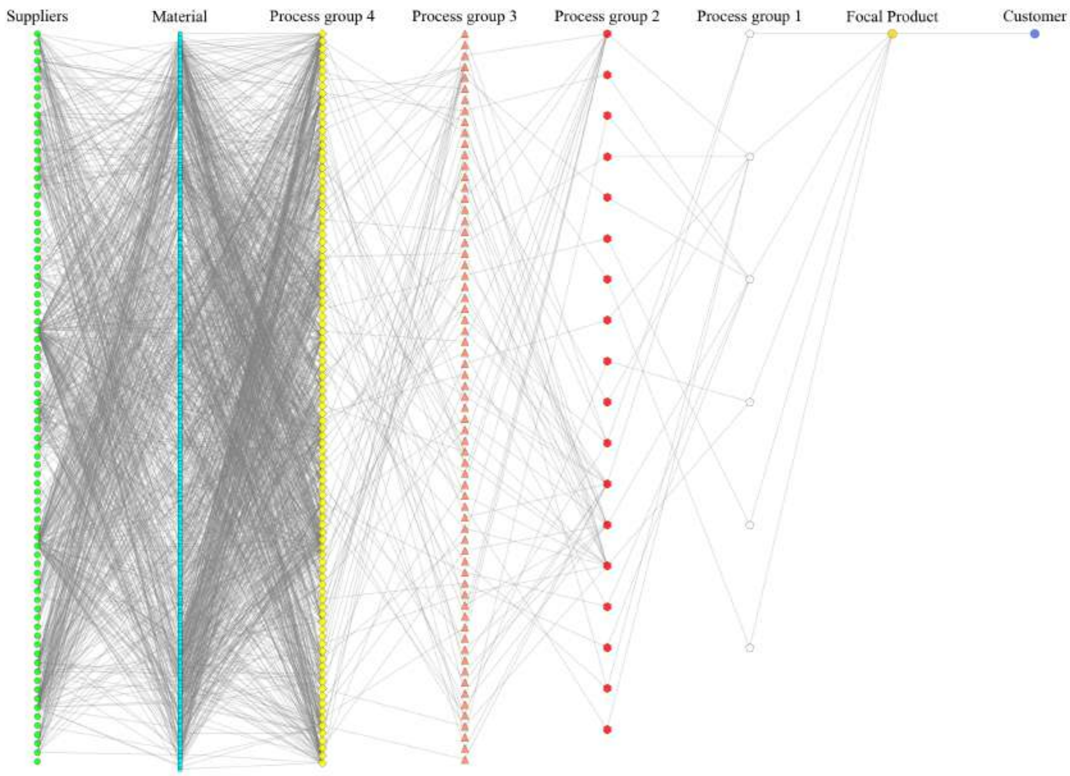

Fig. 3. Process-integrated network of the focal product

Our study does not have no limitations. Data quality and completeness vary across layers. While internal data supports detailed modeling of product and process layers, the deep-tier supplier network relies on external sources. The model also does not currently account for financial flows and information flows, which are increasingly critical in supply chain management. While the individual layer is defined, inter-connectivity across layers remains underdeveloped. Stronger cross-layer mappings are essential to investigate ripple effects and disruption overlay, and improve interoperability. Finally, although validated within one leading European manufacturing firm, further research is needed to assess its applicability across industries with different supply chain structures and characteristics.

Future research could focus on enhancing inter-layer integration, improving data accessibility for the deep-tier supply network layer, and validating the framework across industries and supply chain configurations. Modeling financial and information flow networks could further enrich the analytical depth of our proposed approach. Developing simulation platforms with disruption scenarios and analytics tools could enable more informed decisions in managing ripple effects and disruption overlays. Additionally, identifying network metrics and attributes to predict nexus nodes presents a promising research direction.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Dr. Ilya Jackson for his contributions to data collection related to the mapping of Layer 1 in this study. The present work was conducted in the framework of the project ACCURATE (project ID: 101138269), supported by the Horizon Europe Framework Programme, under grant agreement number 101138269, HORIZON-CL4-2023-TWIN-TRANSITION-01-07.

REFERENCES

Basole, R.C. and Bellamy, M.A. (2014). Supply network structure, visibility, and risk diffusion: A computational approach. *Decision Sciences*, 45(4), 753–789.

Bier, T., Lange, A., and Glock, C.H. (2020). Methods for mitigating disruptions in complex supply chain structures: a systematic literature review. *International Journal of Production Research*, 58(6), 1835–1856.

Choi, T.Y., Dooley, K.J., and Rungtusanatham, M. (2001). Supply networks and complex adaptive systems: control versus emergence. *Journal of Operations Management*, 19(3), 351–366.

Choi, T.Y. and Hong, Y. (2002). Unveiling the structure of supply networks: case studies in honda, acura, and daimlerchrysler. *Journal of Operations Management*, 20(5), 469–493.

Culot, G., Podrecca, M., Nassimbeni, G., Orzes, G., and Sartor, M. (2023). Using supply chain databases in academic research: A methodological critique. *Journal of Supply Chain Management*, 59(1), 3–25.

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

Flynn, B.B., Koufteros, X., and Lu, G. (2016). On theory in supply chain uncertainty and its implications for supply chain integration. *Journal of Supply Chain Management*, 52(3), 3–27.

Habibi, F., Chakrabortty, R.K., Abbasi, A., and Ho, W. (2025). Investigating disruption propagation and resilience of supply chain networks: interplay of tiers and connections. *International Journal of Production Research*, 1–23.

Harland, C. (2021). Discontinuous wefts: Weaving a more interconnected supply chain management tapestry. *Journal of Supply Chain Management*, 57(1), 27–40.

Ivanov, D. (2023). Intelligent digital twin (idt) for supply chain stress-testing, resilience, and viability. *International Journal of Production Economics*, 263, 108938.

Ivanov, D. (2024a). Conceptualisation of a 7-element digital twin framework in supply chain and operations management. *International Journal of Production Research*, 62(6), 2220–2232.

Ivanov, D. (2024b). Exiting the covid-19 pandemic: Aftershock risks and avoidance of disruption tails in supply chains. *Annals of Operations Research*, 335(3), 1627–1644.

Ivanov, D. (2024c). Supply chain resilience: Conceptual and formal models drawing from immune system analogy. *Omega*, 127, 103081.

Ivanov, D., Sokolov, B., and Kaeschel, J. (2010). A multi-structural framework for adaptive supply chain planning and operations control with structure dynamics considerations. *European Journal of Operational Research*, 200(2), 409–420.

Kim, Y., Chen, Y.S., and Linderman, K. (2015). Supply network disruption and resilience: A network structural perspective. *Journal of Operations Management*, 33-34, 43–59.

Majumder, P. and Srinivasan, A. (2008). Leadership and competition in network supply chains. *Management Science*, 54(6), 1189–1204.

Namdar, J., Blackhurst, J., Zhao, K., and Song, S. (2024). Cascading disruptions: Impact of modularity and nexus supplier predictions. *Journal of Supply Chain Management*, 60(3), 18–38.

Nguyen, P., Ivanov, D., and Sgarbossa, F. (2023). A digital twin–based approach to reinforce supply chain resilience: simulation of semiconductor shortages. In *IFIP International Conference on Advances in Production Management Systems*, 563–576. Springer.

Olivares Aguila, J. and ElMaraghy, W. (2018). Structural complexity and robustness of supply chain networks based on product architecture. *International Journal of Production Research*, 56(20), 6701–6718.

Simchi-Levi, D., Schmidt, W., Wei, Y., Zhang, P.Y., Combs, K., Ge, Y., Gusikhin, O., Sanders, M., and Zhang, D. (2015). Identifying risks and mitigating disruptions in the automotive supply chain. *Interfaces*, 45(5), 375–390.

Zhang, L., Brusset, X., Ma, Y., Zhang, F., and Qiao, P. (2024). Resilience of interdependent supply chain networks design and protection under the ripple effect. *International Journal of Production Research*, 62(24), 8651–8677.

Zhao, K., Zuo, Z., and 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.