An Adaptive Supply Chain Stress Testing Framework with Deep Learning

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Abstract. Since the COVID-19 pandemic, supply chain disruptions have become the biggest risk to the continuity and stability of the global economy. Therefore, assessing the vulnerability of supply chains and developing the best mitigation plans for high-impact disruptions to enhance supply chain resilience is crucial to the survival of public and private organizations. In this paper, we propose a conceptual framework for diagnosing the vulnerability of suppliers, logistic providers, and commodities for any size of multi-tier supply chain networks for private and public bodies. The framework is based on a supply chain digital twin that will be formed with the industrial Internet of Things technology for accessing field data, machine learning models for disruption prediction, simulation methods for disruption scenario analysis, and optimization methods for developing mitigation plans to minimize the impact of anticipated disruptions. The framework also exploits a deep learning-based surrogate model of the digital supply chain twin.

Keywords: Supply chain resilience; Digital twin; Machine learning; Simulation; Optimization; Deep learning.

1 Introduction

Supply chain disruptions have become the dominant factor affecting the global economy since the start of COVID-19. Returning to a "new normal" still looks far away due to ongoing social, political, economic, and environmental problems, as seen from the Global Supply Chain Pressure Index at the Federal Reserve Bank of New York [8]. Therefore, closely monitoring supply chain stakeholders, measuring and predicting risks on each of them, and developing fast and accurate mitigation plans are crucial for ensuring supply chain resiliency.

Since the beginning of the 1990s, global supply chains have been structured to prioritize the low cost in a considerably disruption-free global economy. Consolidating suppliers, applying lean principles, and reducing inventory levels have been the main objectives for strengthening companies' competitiveness. However, COVID-19 and the last decade's historical disruptions such as the 2011

Japan Tsunami, the 2019 deadly Typhoon Mangkhut, the 2022 Ever Given container ship blockage at the Suez Canal, and the ongoing war in Ukraine showed the vulnerability of the global supply chain. Recently, the World Economic Forum [1] listed the "collapse of a systematically important supply chain" as one of the most important risks in the global economy for the next decade [1]. Hence, a paradigm shift from "cost first" to "resiliency first" is being observed in supply chain practitioners [5].

Monitoring national supply chain resiliency and guiding public and private organisations toward strengthening their supply chain are also becoming important priorities of governing bodies as well ([10],[4], [2], [3]). Strengthening global supply chain resiliency is also one of the thematic areas of UN Sustainable Development Goals as depicted in targets 9.1, 9.a and 9.b [7].

Therefore, there is an emerging need for public and business organizations tools for (1) monitoring and evaluating the vulnerability of their supply chains (2) re-design and improving supply chain networks to minimize the impact of disruptions, recommending alternative mitigation plans to make them more resilient to unexpected shocks, (3) without sacrificing sustainability particularly in "energy resiliency" which aims to increase the share of renewable energy sources when designing supply chain networks and minimize resource/energy usage ([6]).

In this paper, we will present an adaptive supply chain testing framework that aims to support public and commercial organisations to enhance their supply chain resilience. In Section 2 findings based on interviews conducted with experts from various countries and industries for requirement analysis and justifying the need for a novel approach are summarized. The proposed framework is discussed in Section 3. Finally, the paper concludes in Section 4 with the significance of the proposed framework and its expected business and societal impact.

2 Industry Perspective

To understand current practices, organisation maturity, and needs, we conducted 16 interviews from various countries and industries. While the majority of the interviewees are from Ireland (8), this number is followed by the US (3), Sweden (2) Germany, India, and Turkey, one from each. A significant number of interviewees were from the manufacturing industry (7), followed by consultancy (5) and retail, software, aviation, and higher education, one from each of them. Interviewees are representing organizations from 5 to half a million of size from varying positions; supply chain manager, analytics team lead, analyst, project manager, professor, and CEO.

All interviewees agreed that the global economy is now living in a permanent disruption era. From SME to multi-national scale, stakeholders noted the difficulty of monitoring their tier-2 and further upstream suppliers. Therefore, supply chain visibility and integration are the primary focus areas for resilience enhancement. The majority of stakeholders noted the lead time and perfect order rate as metrics they use for monitoring supplier performance and did not point to any resiliency-related performance measure. The resilience of a supplier is understood as their trustworthiness but the impact of their disruption on the overall supply chain, the ripple effect, is not considered comprehensively. Because of that, resiliency mitigation actions noted are mostly reactive rather than proactive. Nevertheless, there is a consensus on several actions; allocating buffer stocks and dual-sourcing and re-shoring but methods to identify the right decisions on these rely on expert opinion. Although Environmental, Social and Governance (ESG) concerns are taken into account during operations management as noted by two stakeholders, none of them pointed their integration into resiliency enforcement efforts.

Interviews and relevant academic literature identified that for end-to-end supply chain resilience, there is a need for (1) a mechanism to anticipate the likelihood of disruption scenarios (2) evaluating the impact of each scenario on the whole value chain (3) ranking the severity of each scenario and node in the supply chain for all tiers (4) preparing and validating mitigation plans on dual sourcing, buffer allocation, re-allocating capacities and transportation of entities (5) yet being robust enough for anticipated disruption scenarios while respecting economic, sustainability and societal concerns (6) and develop the best course of action in a computationally fast way to reduce disruption response time.

It is noted during the interviews that industry representatives can describe only a few aspects of the broader challenge, supply chain resiliency, and testing supplier vulnerabilities. The majority of the interviewees were unable to distinguish the disruptions originated from the customer side (downstream, bullwhip effect) and the supplier side (ripple effect). However, there is an overlapping emphasis from all participants on “lead time variability”, “delivery on time full” and “demand fluctuations” as the main disruption scenarios as well as “buffer inventory” and “dual sourcing” as pre-disruption preparation methods. One participant from the pharmaceutical industry declared that they become aware of supplier problems only when they inform them and it is already too late to find the best mitigation actions. Another interviewee who is a consultant and has experience in many public and commercial organisations pointed out the importance of ripple effect for critical industries like chemical manufacturing which could cause a compound effect at downstream of the chain. Another interviewee from a global manufacturing company noted that they have a dedicated team to monitor and mitigate supplier-side disruption, however, their team is capable of tracking only tier-1 suppliers. Furthermore, tracking is handled through a shared digital portal where up-to-date performance indicators are provided by suppliers manually which helps his team to see the trends but in case of an unexpected disruption, communication and mitigation planning are handled through e-mails and phone calls. Indeed, this feedback overlaps with another stakeholder that they want to progress from unknown-unknown to unknown-known capability which means being able to be prepared (i.e. know possible impacts and what to do) for disruptions that are not known the timing.

2.1 State-of-the-art industrial solutions

Industry leader solutions for supply chain resilience analytics mentioned by practitioners during our interviews such as Everstream Analytics, Sphera, and Prewave are promoting their tools with alert notification and monitoring capabilities. While alert notifications rely on web scrapping from social media and news from the locations of suppliers, monitoring capability exploits the information sharing with suppliers. Risk analysis provided to users in these solutions uses qualitative data obtained from regular surveys of suppliers and conventional key performance indicators (KPI) like lead time, on-time delivery, and defect rate. However, node and flow complexity, density, and node criticality of the network are ignored. Besides, none of them quantifies the ripple effect caused by the disruption of each supplier along with environmental and societal impact. Furthermore, the mentioned solutions provide a rigid framework that is not possible to customize or integrate with advanced analytic methods as depicted in the previous section. Currently, only AnyLogistix software offers a digital solution that integrates the decision and simulation modeling capabilities for supply chain risk analytics. However, AnyLogistix also has limitations of relying on commercial decision analytics tools, the shallow learning curve, and lack of customization for different business rules, situational awareness, and modularity of technology used.

The framework proposed in this paper differentiates from state of art tools by (1) being modular for the technology used (2) relying on open source tools (2) integrating risk prediction, stress testing, mitigation planning, and validating (3) minimizing the complexity of the analytics methods for practitioners (4) including network and sustainability based KPIs for a holistic view on the supply chain resiliency.

3 Adaptive Supply Chain Stress Testing Framework

The adaptive supply chain stress testing framework presented in Fig. 1 consists of several components sequentially interacting with each other. The solution provides a mechanism for converting supply chain geospatial data and bill of material (BOM) into a graph model. While each node represents a component/subassembly/product/service in BOM and its relevant facility, edges represent the eligible material flow between facilities and between nodes in BOM. Next, for each facility node, the most likely disruption duration and probability of occurrence is computed through stakeholder historical records and publicly available data via web scraping. Disruption scenarios arefed into a decision model to find the best resource allocation (i.e., mitigation) plan that minimizes the economic, environmental, and societal impact of those scenarios that is adapted from [9]. Next, a high-fidelity discrete event simulation model is used to validate the mitigation plans considering compound disruption scenarios, complex interactions between nodes, and the behavior of the supply chain under uncertainty over time. Diagnosed discrepancies in the mitigation plan from the decision model and their realization in the simulation model are resolved with a feedback loop between the two models that increases the robustness of the plan. The developed combined decision and simulation model mechanism is used for training a metamodel (artificial neural network, ANN) which enables stakeholders to use the stress testing framework without needing decision and simulation modeling tools.

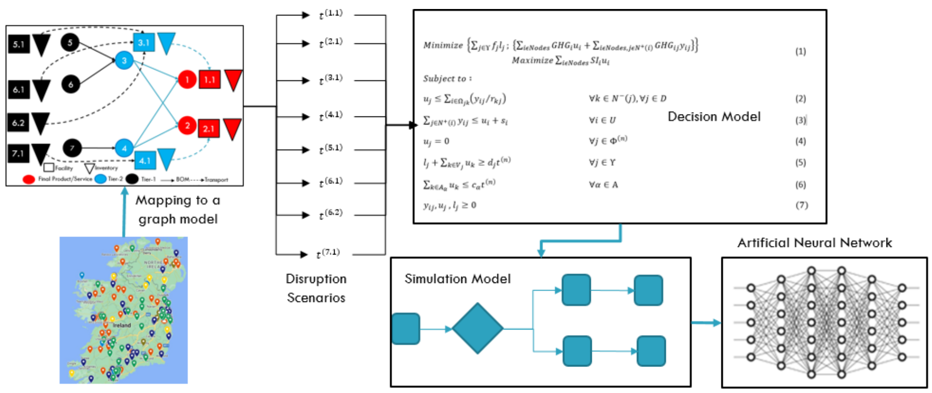

Fig. 1. Adaptive Supply Chain Stress Testing Framework

4 Conclusion and the Future Research

Recent global disruptions showed that using only delivery performance like lead time, on-time delivery, defect rate or financial health of suppliers is not sufficient as indicated during industry interviews. Also, it is pointed out that, supply chains, particularly ones spread globally require more holistic indicators to test the strength of the supply chain. There is a strong need for anticipating and quantifying the impact of disruptive events. The proposed solution has the potential to address these points by incorporating supply chain network-related KPIs and considering compound disruption scenarios while developing mitigation plans taking into account financial, environmental, and social concerns. Uncertainties in lead times, operation durations, and availability of capacities are putting significant stress on supply chains as noted during the interviews. The proposed solution is incorporating anticipated uncertainties with the high-fidelity dynamic discrete event simulation. The COVID-19 pandemic also showed the need for fast reconfiguration of existing manufacturing facilities for producing urgent health products like ventilators. This unexpected global disruption requires reconfiguring the whole supply chain in a short period as well. The proposed tool has the potential to support governmental agencies, healthcare, and industry in their manufacturing re-purposing efforts during crisis times.

The sequential structure of the proposed framework allows the development of the solution through the waterfall principle. However, individual components will be developed with continuous feedback from engaged industry stakeholders to make sure they are in line with the challenges identified. Several supply chain networks from academic literature will be used to generate test instances. Disruption scenarios will be generated based on these instances as well as a decision model to develop mitigation plans and validate via a discrete event simulation model. State of art industrial solutions mentioned in Section 2 will be used for benchmarking the developed solution.

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References

[1] World Economic Forum. *Global Risks Report 2023*. URL: https://www.weforum.org/reports/global-risks-report-2023. (accessed: 23.09.2023).

[2] Germany. *German Supply Chain Act,* URL: https://www.politico.eu/article/germany-supply-chain-new-yearnew-%20rules-comes-into-force. (accessed: 23.09.2023).

[3] Irish Government. *Ireland's National Recovery and Resilience Plan.* URL: https://www.gov.ie/en/publication/d4939-%20national-recovery-and-resilience-plan-2021/. (accessed: 23.09.2023).

[4] UK Government. *The UK Government Resilience Framework.* URL: https://www.gov.uk/government/publications/the-uk-government-resilience-framework. (accessed: 23.09.2023).

[5] Dmitry Ivanov and Alexandre Dolgui. "Stress testing supply chains and creating viable ecosystems". In: *Operations Management Research* 15.1 (June 2022), pp. 475–486.

[6] Dmitry Ivanov et al. "A survey on control theory applications to operational systems, supply chain management, and Industry 4.0". In: *Annual Reviews in Control* 46 (2018), pp. 134–147.

[7] United Nations. *UN Sustainable Development Goals.* URL: https://sdgs.un.org/goals. (accessed: 23.09.2023).

[8] Federal Reserve Bank of New York. *Global Supply Chain Pressure Index.* URL: https://www.newyorkfed.org/research/policy/gscpi. (accessed: 23.09.2023).

[9] David Simchi-Levi et al. "Identifying Risks and Mitigating Disruptions in the Automotive Supply Chain". In: *Interfaces* 45.5 (2015), pp. 375–390.

[10] Whitehouse. *Economic Report of the US President.* URL: https://www.whitehouse.gov/wpcontent/%20uploads/2022/04/ERP-2022.pdf. (accessed: 23.09.2023).