Building Resilience in Industry 4.0 Smart Supply Chains: Rapid Distributed Information Dissemination using Decentralized Systems

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Abstract

Business Problem

Supply chain disruption is viewed as the top risk to the business performance and a key priority for 62% of organizations according to a report by Capgemini Research Institute (CRI, 2020). Based on the cause, the major groups of disruptive events from a real-time monitoring and predictive capability perspective (i.e., in the current research scope) identified as 4D effect (Disaster, Delay, Damage, Demand change) include Disasters (natural or manmade), Operational Delays or Difficulties (e.g., congestion), Damage to Systems (e.g., information systems or equipment breakdown) and Demand pattern changes resulting in forecasting inaccuracies. At a basic level, resilience refers to the ability to recover from or adjust to misfortune or change - the ability of a company and supply chain to "bounce back" after an event (Schlegel & Trent, 2014). In this research we have focused on the impact of technology on the twin Drivers of Resilience - Agility and Visibility. Industry 4.0 (I4.0) with real-time capabilities, provides the needed technology backbone for enabling rapid decision-making in the face of severe disruptions, improving agility and thus contributing to resilience Extant literature thus suggests that rapid information and ubiquitous visibility in I4.0 contribute to building resilience and support the role of real-time technology in enabling visibility and agility. Real-time information, a key principle in Industry 4.0, needs active and continuous data monitoring for processing information rapidly. Rapid data generation, transmission, and processing are technology ingredients contributing to visibility and agility.

Purpose and Motivation

This study aims to understand and explore the role of emerging distributed real-time technologies under I4.0 for enabling visibility and agility, the twin drivers for developing supply chain resilience (SCR). The research builds upon the conceptual studies and the propositions in supply chain management on the role of technology in improving resilience by providing a substantive (mid-range) theory on the phenomenon of technology-enabled SCR. Given the multidimensional nature of the problem, it needs focused interdisciplinary research to elaborate on the role of technology as a driver for SCR. Information communication and networking technologies (ICT) help in the

end-to-end visibility of the supply chain in real-time, providing data for AI-driven decisions, such as sensor data and logistics goods movement tracking. Therefore, technology can play a crucial role in disruption resilience, and its potential is not yet fully realized as the digitalization of the supply chain is still in the early stages. The extant literature is fragmented and spread across disparate areas on the role of technology in general and decentralized and distributed information technology and systems in particular in developing supply chain resilience. The extant literature also discusses the potential of rapid real-time information sharing in the early detection of SC disruptions, thereby triggering rapid response and ensuring adaptability or agility.

Across these disparate studies, an integrative theoretical framework that can explain and predict the role of technology in building supply chain resilience across the different stages of disruption - detection, response, and recovery, is missing. To address the gap between academic research and practitioners' needs, we undertake an empirical study that develops a generalization and abstraction framework on the role and applicability of technology in building supply chain resilience (SCR). To our knowledge, there has been no comprehensive research on the role of distributed information processing using decentralized information and communication technology (ICT) in ensuring rapid information flow, agility, visibility, and resilience.

Methodology

Our qualitative research for theory development is done in two phases - phase 1 is grounded theory research (GTR) for a substantive theory building and phase 2 is retrospective case analysis/case study research for validating the theoretical framework against real business scenarios. We undertake a Retrospective Case Analysis using a secondary case data of a real organization to improve the analytical generalizability of the developed theory and check the applicability of the concepts and their interrelations as a whole. We also undertake design science research (DSR), with the grounded theory developed as the kernel theory that formulates a solution for the stated business and technical problem using the theory as the foundation. The DSR develops a technology strategy and architecture as an artifact that can address business and technical problems in ensuring rapid information sharing using distributed systems and decentralized local decision-making.

Findings and Contribution

We focus on the role of distributed and decentralized technologies among the vast technology landscape of I4.0. We highlight three such technologies whose roles in SCR are relatively under-researched - Industrial Internet of Things (IIoT) as sources of distributed data generation, 5G or next generation connectivity for high-speed communication, and edge or distributed cloud (fog) computing for AI-driven processing and autonomous decision-making. Taken together, these three technologies represent the emerging technologies comprising data generation, data transmission, and data processing and insights generation. Based on our extensive and rigorous GTM-based analysis of twenty-eight theoretical and discriminative samples we develop a parsimonious supply chain disruption resilience theory with I4.0 distributed and decentralized technology backbone as the core concept and further expand this core concept into a technology theory. The supply chain disruption resilience theory explains and predicts how technology enabler antecedents such as a connected and collaborative supply chain, culture for information sharing, and I4.0 technology capability contribute to technology transformation enablement, enterprise risk management, supply chain collaborative network, and supply chain strategy enablement, that together contribute to technology transformation-led value creation in the form of visibility and agile proactive and reactive response. The technology theory highlights the importance of decentralization-centralization cohabitation and hub and spoke model of information distribution using the distributed computing paradigm and next generation high speed connectivity as key constituents for rapid information sharing. The design science research takes the distributed design framework and the technology theory for developing an IS theory and instantiation in the form of a design and architecture for addressing wicked problem of developing supply chain resilience, addressing the technology constraints. The theory developed is validated by multiple means, using the grounded theory's intrinsic constant comparison, the evaluation frameworks suggested for grounded theory by its proponents, the theory evaluation framework of Weber (2012), and last but not the least, validating the theory retrospectively in a real organization case study that went through severe supply chain disruption.

The key contribution of this research apart from the parsimonious theory incorporates a strategic roadmap in technology systems design focusing on supply chain performance and resilience-building as outcome. The study is of significance for the practitioners as it focuses on developing a technology transformation strategy and design architecture including design propositions that can be validated through subsequent action research. Future research opportunities are identified.

8. Conclusion

Summary and Key Contribution

This research investigates the potential of emerging Industry 4.0 (I4.0) technologies to enhance supply chain agility, visibility, and resilience. The study employs a mixed-methods approach, combining Grounded Theory and Case Study methodologies.

RQ1: The first research question explores the specific roles that I4.0 technologies can play in achieving supply chain disruption resilience. Grounded Theory is utilized to develop a new theory of Supply Chain Disruption Resilience Theory (SCDRT) by analyzing data related to emerging I4.0 technologies. This theory is evaluated and extended using one critical secondary case study.

RQ2: The second research question delves into how decentralized information processing and distributed decision-making technologies can facilitate rapid and pervasive information dissemination, thus contributing to supply chain resilience. Design Science Research is employed, drawing from nascent IS Theory and Design Science Research Activities (DSRA) framework. This approach develops an IS theory focusing on the transformative potential of technology in shaping supply chain resilience. The research also produces a set of design propositions and a digital footprint agnostic architecture addressing the "wicked problem" of how technology can transcend the constraints and limitations to influence supply chain resilience.

Research and Policy Implications:

- Development of a new theory (SCDRT) grounded in data for a new and emergent phenomenon and extension of the proposed theory using secondary case study research.
- Development of a Technology (IS) theory focusing on the transformative potential of technology in developing supply chain resilience.
- Creation of a set of design propositions and technology architecture for SC Resilience.

Managerial Implication:

Developing a framework highlighting possible role of technology in developing supply chain resilience driving technology evaluation and selection decisions and identification relevant factors driving and contributing towards resilience and their interplay with technology that can be actionized in a real organizational and supply chain context. The research can also be extended

across other domains such as smart city, connected and intelligent logistics, smart ports for digital transformation enablement.

Future Research

- We suggest design science research (DSR) that establishes the efficacy of distributed computing in rapid decision-making using an experimental setup. The experiment can compare the decision-making process using cloud computing and edge computing with real-time data and an AI-based model that can detect anomalies as operational disruption in a particular context in a resource-constrained environment
- We suggest an empirical approach with a survey or case study research-based validation of the constructs of our substantive theory. In particular, the role of I4.0 technology in developing supply chain resilience can be empirically validated using constructs such as collaboration, agility (response), visibility, risk management, information flow enhancing factors, emerging technology adoption, and capability versus need assessment, supply chain strategy of responsiveness as either moderators or mediators, and organization culture, technology capability, and connected supplier network as antecedents. The role of early warning and continuous monitoring in developing visibility needs attention.
- Future research should focus on developing global visibility using supply chain network mapping. A few suggestions have been provided in our DSR which could be expanded, such as using social network analysis to map the nodes and the edges as the facilities and their linkages, and spectral clustering to detect a community for rapid communication
- Future research can delve deeper into AI capabilities and applications in developing visibility and agility, particularly in real-time insight generation and prediction on disruptions based on early warning indications, such as demand pattern changes
- The role of constraints, especially external environmental constraints and internal constraints such as employee skills and expertise need to be empirically established
- Impact of product-technology innovations and technology disruptions on developing resilience need to be explored. An interesting research question would be whether innovative organizations are more equipped to handle unknown risks and are resilient
- The Role of human-AI collaboration, particularly the construct of human in the loop on critical automated decisions, needs to be explored in the context of Industry 4.0

- Exploratory Case Study and Design Science Research on the impact of architectural elements of distributed and decentralized systems such as distributed data generation, high-speed connectivity, and processing near the data source on the speed of decisions, cost minimization, and sustainable practices and supply chain resilience
- Organizational data privacy protection and its impact on device data processing, inter-organizational sharing, and the design of communication infrastructure across supply chains need to be evaluated in the light of regulatory policies
- Uncovering the challenges of using distributed and decentralized systems in the resource-constrained organizations and impact of risk sharing and investment sharing measures among the supply chain partners such as resource-pooling can be an area
- One important variable that appears in our study is the role of centralization and decentralization cohabitation in information sharing. This variable and its impact on various supply chain outcomes such as performance, resilience, and sustainability can be explored further using empirical analysis such as case study research

Limitations

Our research analyzes twenty-eight theoretical and discriminative samples to achieve saturation. However, more practical insights could be obtained from the primary data provided by the practitioners. Hence future research should provide more importance to the theoretical samples that include practitioners who are experts in supply chain disruption resilience and in the application of technology. Future research should also focus on the fitment of the framework in an actual organizational context through a field study. It is important to get the perspectives of the organization on the technology framework first hand, rather than an interpretation of the secondary data post facto. Extending our design science research that proposes an architecture and a digital transformation strategy, it would be worthwhile to do action research in a limited context of a supply chain, such as a warehouse, to study the impact of rapid real time decentralized information from the distributed systems. Last but not the least, our research journey started two years back when there was a dearth of theoretical frameworks on technology in supply chain resilience. During this journey, especially in the recent period, more conceptual work has been done on the role of technology in building resilience (Wu et al., 2024) that could be further assessed.

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Appendix

Appendix A. Additional References and Data Sources for Case Study Research

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- Flex Ltd. (FLEX) 10-K Annual Report May 2022 (last10k.com)
- Flex's Global Lighthouse Network Factories | Flex
- Flex - Flex Factory in Althofen, Austria Admitted into World Economic Forum Global Lighthouse Network