An Investigation of Digital Twin adoption for enhancing Supply Chain Resilience

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Abstract

Digital twin plays a crucial role in mitigating supply chain disruptions and building future supply chains with resilience capabilities. This research paper utilized qualitative interviews and qualitative survey to examine the impact of supply chain digital twin in enabling supply chain resilience and develop a roadmap for digital twin adoption. The contribution of this research paper includes: 1. development of digital twin adoption roadmap, 2. identification of resilience capabilities developed in supply chain by digital twin adoption. The results from this research indicated that digital twin adoption phases consist of evaluating maturity and current state, digitizing supply chains to improve supply chain connectivity, data generation and value creation, and developing supply chain planning and monitoring platform. This research paper determined that digital twin improves supply chain visibility and decision-making capability during disruption response and recovery. The ability of organizations to modify supply chain network and maintain continuity is improved by insights and plans generated from digital twin. This research identified that digital twin supports an organization in anticipation, response, and recovery stages of supply chain disruption.

Keywords
Supply Chain Resilience, Digital Twin, Internet of Things, Supply Chain Analytics, Decision Support.

1. Introduction

Supply chains support organizations to manufacture and deliver quality products to customers at the right time and right location by leveraging their network, which is crucial for profitability and competitive advantage (Gunasekaran et al., 2001; Kwak et al., 2018; Li et al., 2006). Supply chain continuity can be disrupted by various factors such as global dispersion, node constraints, geopolitical, and weather uncertainties (Blome and Schoenherr, 2011; Brusset and Teller, 2017). Supply chain risk management (SCRM) involves risk identification, risk evaluation, risk mitigation, and risk monitoring (Diabat et al., 2012). Supply chain risks can be operational (quality issues, breakdowns), man-made (tariffs, strikes), or natural disasters (floods) (Diabat et al., 2012; Faisal et al., 2006). The top vulnerabilities in supply chain includes supply disruptions, dependence on international suppliers, and loss of reputation (Chowdhury and Quaddus, 2015).

COVID-19 exposed vulnerabilities, bottlenecks, inefficient SCRM practices in supply chain, and impacted supply chain and organizational performance (Ivanov, 2020). Supply chain continuity and building resiliency became the main focus for C-Suite and top management due to recent disruptions such as semiconductor shortages, Suez Canal blockage, and COVID-19 (Roh et al., 2021; Wayland, 2021). Organizations are developing digital supply chain capabilities for managing supply chains in volatile, uncertain, complex, and ambiguous (VUCA) environment (Ardito et al., 2019; Birkel and Hartmann, 2020). Supply chain digital twin and associated technologies are interventions that can improve supply chain resilience (Ivanov and Dolgui, 2020). Due to recent disruptions, companies faced supply shortages, manufacturing shut downs, and revenue loss in billions (Dunn, 2021; Roh et al., 2021; Wayland, 2021). These impacts on revenue made organizations to rethink their supply chain strategy and invest in supply chain technologies to maintain continuity (Ivanov, 2021).

Advanced technologies are necessary to manage supply chain and build resilient supply chains (Durach et al., 2015; Hosseini et al., 2019). Industry 4.0 ecosystem consists of various technologies such as Internet of Things (IoT), big data analytics, augmented reality, virtual reality, blockchain, additive manufacturing, and digital twin (Asdecker and Felch, 2018; Bär et al., 2018). Industry 4.0 technologies, predominantly Internet of Things (IoT), Big Data Analytics and Digital twin technology, boosts supply chain disruption management capability (Birkel and Hartmann, 2020; Papadopoulos et al., 2017). IoT helps in monitoring of supply chains and sharing of real-time information with supply chain partners (Dubey et al., 2019).

Industry 4.0 technology can play a role in improving supply chain resilience (Ralston and Blackhurst, 2020). Lack of solid framework that provides guidance on IoT and other technologies adoption in supply chain context is limiting the wide-ranging adoption of Industry 4.0 technologies (Ben-Daya et al., 2019). Managerial guidance and implication research are required in the supply chain and Industry 4.0 area (Frederico et al., 2019). Therefore, to accelerate the adoption of digital twin in manufacturing organizations, efforts are made in this research to develop a roadmap and provide strategic guidance for supply chain practitioners.

This research aims to fill the above discussed research gap and examines the adoption of digital twin for improving supply chain resilience. The objective of this research is to investigate the benefits of adopting digital twin in supply chains from the perspective of building resilience. The research objectives of this study are divided into the following sub-objectives: 1. Develop a roadmap for adoption of digital twin 2. Determine the resilience elements enabled in supply chain by adopting digital twin technologies, and 3. Investigate the impact of digital twin in helping organizations to anticipate, respond, and recovery quickly from supply chain disruptions. After this section, the paper is organized into five major sections. The second section discuss the literature related to supply chain resilience and digital twin adoption. The third section covers the methodology used in this research paper. The fourth section covers the data collection and the data analysis process. The fifth section includes the results from this research and the discussions. The final section covers the conclusions and the research contribution of this research paper.

2. Literature Review

This section covers the literature related to supply chain resilience, digital twin adoption, and research studies in the area of improving supply chain resilience through digital twin technologies. Supply chain resilience is the “adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior to the disruption” (Tukamuhabwa et al., 2015, p. 5599). Organizations cannot avoid supply chain disruptions, but they can build capabilities and create contingency plans that support them to navigate disruptions without impacting supply chain performance (Golgeci and Y. Ponomarov, 2013).

Supply chain disruption management is typically classified into three phases – readiness, response, and recovery (Chowdhury and Quaddus, 2017; Holcomb and Ponomarov, 2009). Readiness phase is the pre-disruption stage whereas the post-disruption stage includes response phase and recovery phase (Chowdhury and Quaddus, 2017). Creating readiness for the disruption is a proactive strategy where firms proactively prepare for supply chain responses (Holcomb and Ponomarov, 2009). On the other hand, without readiness, firms will react to the event only when they are disturbed by a disruption, and this approach is considered as a reactive strategy in disruption management (Tukamuhabwa et al., 2015). Similarly, the ability to reconfigure supply chains and adapt to changes during disruptions defines the resilience level of supply chains (Ambulkar et al., 2015).

Continuous sensing and monitoring of supply chains enable quick response to disruptions. Quick response impacts the success rate of supply chain reconfiguration capability and enhances resilience (Lee and Rha, 2016). Internet of Things and Supply Chain Analytics improves the readiness capability of supply chain (Birkel and Hartmann, 2020; Dubey et al., 2019). Designing supply chains for maintaining continuity is crucial for sustaining supply chain performance and revenue growth (Gunasekaran et al., 2001; Kwak et al., 2018; Li et al., 2006). Similarly, organizations can improve their supply chain collaboration and risk management culture across the supply chain which improves resilience (Chowdhury and Quaddus, 2017; Lee and Rha, 2016).

Digital transformation requires determination of current maturity state, future/ target state, and gaps to address in order to achieve the expected maturity level (Bär et al., 2018). Some of the factors to consider in evaluating maturity are human resource management, IT maturity or technology gaps, and organizational processes (Frederico et al., 2019). The evolution of cyber physical systems consists of stages such as connection, conversation, control, and optimization (Lee et al., 2015). Similarly, implementation of smart supply chain consists of few maturity stages (Wu et al., 2016). There are five maturity states in converting IoT data to business value which includes data generation, data management, deploying data visualization dashboards, applying analytical algorithms, and developing a culture to utilize data in decision making (Arunachalam et al., 2018). Organizations should nurture capabilities for achieving value from big data gathered from IoT and various supply chain data sources (Brinch, 2018).

There are only few research studies that investigated the use of Industry 4.0 technologies for improving supply chain resilience. Ralston and Blackhurst (2020) utilized qualitative case study and determined that Industry 4.0 improves supply chain resilience with warning capability and process automation, which improves the efficiency of supply chain and disruption management. Ivanov and Dolgui (2020) proposed a conceptual model of digital twin and illustration of digital twin usage in disruption response. Birkel and Hartmann (2020) determined that IoT improves supply chain risk management capability by improving data generation and data processing capability. This enables real-time data driven decisions in supply chain which reduces uncertainty in decision making process. Dubey et al. (2019) found that data analytics capability improves supply chain resilience. Therefore, digital twin and Industry 4.0 technologies such as IoT and big data analytics can improve supply chain resilience.

Some of the authors have called for an in-depth investigation on organizations that transformed their supply chain by adopting these advanced technologies (Hosseini et al., 2019). Conducting interviews with organizations and managers involved in the transformation projects will develop theoretical insights and implications for supply chains undertaking the digital transformation projects (Bienhaus and Haddud, 2018). The review of literature has shown that there is a gap (in literature) in the investigation of supply chain digital twin adoption for building resilient supply chains (Ivanov and Dolgui, 2020). Therefore, this research focused on addressing this literature gap and adopted a qualitative inquiry approach to investigate the adoption of digital twin for improving supply chain resilience. The next section covers the research methodology utilized in this research paper.

3. Research Methods

A qualitative research method is ideal for adding knowledge into the topic and generate theory or framework for further testing and refinement (Meredith, 1993; Tukamuhabwa et al., 2015). This study selected inductive approach for theory development (Randall and Mello, 2012). The primary research methodology selected for this study is qualitative interview and qualitative survey among experts in the field of supply chain and advanced supply chain technology. The research methods and the steps carried out in this research are shown in Figure 1. This study has conducted survey and expert interviews simultaneously to gather data. Once, the data was gathered from surveys and interviews, the data analysis has been carried out separately for the survey and interviews. Then, the analysis findings from survey and interviews have been integrated to develop the themes and framework reported in the result section of this paper. The data collection approach and participants demographics are covered in the next section.

Figure 1. Research methodology used in the research

4. Data Collection

A survey instrument was created in Qualtrics tool with open-ended qualitative questions for gathering experts' opinions. The survey instrument categorized questions into major sections. First section included questions regarding the advantages and capabilities gained in supply chain by digital twin adoption. Second section consisted of questions seeking the participants opinion on the adoption roadmap of supply chain digital twin. Third section included questions regarding the demographic information of participants.

Similarly, an interview guide was developed for conducting the interviews with the experts. The questions were focused on 1. resilience capabilities or elements gained in supply chain by digital twin adoption, 2. phases in supply chain digital twin adoption and technology adopted in various phases. The interview guide also encompassed questions for understanding company's appetite and resources established for resilience activities. Both interviews and survey are designed from a qualitative perspective to gather opinion of experts in the field of digital twin and supply chain.

The participants were selected from various backgrounds in manufacturing supply chain (United States) who worked on adopting digital twin technologies or developing a roadmap for such activity. The experts selected for surveys and interviews had experience in Industry 4.0 technologies, supply chain, and technology consulting, most of them are supply chain leaders in manufacturing organization. A total of 11 interviews were conducted and 15 responses were received from the survey. The participant demographics for the interviews and survey is shown in figure 2.

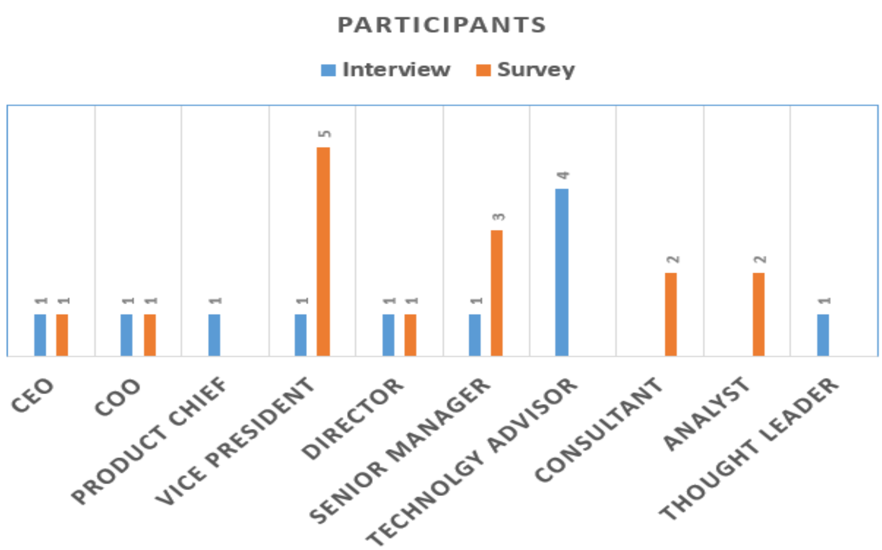

Figure 2. Participant demographics

Among the interview participants, more than 90% of them (10 out of 11) hold managerial or top management position in manufacturing supply chains or supply chain technology companies. 73% of survey participants held either managerial or top management position in their organization. This research collected data from a moderate sized expert group since this research have set criteria to select participants with specialized knowledge in digital twin adoption. Such a sample size has been practiced in the literature for explorative studies through qualitative interviews and surveys where the nature of study demands participants experience and experts opinion through purposive sampling to achieve the research objectives (Kache and Seuring, 2017; Manuj and Sahin, 2011).

4.1 Data Analysis

This section discusses the data analysis process adopted to obtain results. The data gathered from survey and interview were analyzed through content analysis (Krippendorff, 2004). For surveys, the responses were initially grouped by the survey questions. Then, the responses were assigned with codes and then categorized based on similarity (Krippendorff, 2004). For interviews, the data analysis started with reading interview transcripts, generating codes, and assigning codes for the responses (Manuj and Pohlen, 2012). Then, the codes were grouped based on similarity to develop categories and themes. Constant comparison of the data, iterative coding, and aggregation resulted in the emergence of major themes (Manuj and Pohlen, 2012).

5. Results and Discussion

The results from the research study are presented in two sections. The first section discusses the results on digital twin adoption and the phases in supply chain digital twin adoption. The second section summarizes various resilience capabilities developed in supply chain by digital twin.

5.1 Digital Twin Development

The analysis of the data from survey and interviews revealed various phases in the adoption of digital twin. The phases include: 1. Digital twin readiness/current state assessment, 2. Digitizing supply chain and system integration, 3. Data generation, management, and value creation, 4. Constructing supply chain monitoring and planning platform. Table 1 shows adoption phases resulted from data analysis and the level of support from the data for each adoption phase.

Table 1. Digital twin adoption phases

Adoption Phases	**Number of Interviews referenced**	**Number of Surveys referenced**	**Interviews referenced percentage**	**Surveys referenced percentage**	**Support from data**
Digital twin readiness and current state assessment	6	7	55%	47%	Moderate
Digitize supply chain and systems integration	8	10	73%	67%	High
Data generation, management, and value creation	8	9	73%	60%	High
Supply chain monitoring and planning platform	11	12	100%	80%	Very high

5.1.1 Digital Twin Readiness and Current State Assessment

The first step in the digital twin adoption is understanding the current state and technology maturity level of a supply chain. The assessment begins with investigating the challenges in supply chain and requirements for a digital twin capability. The scope of the digital twin needs to be customized based on company's requirements. Creating business case for the digital twin adoption and gaining top management commitment are essential for assimilation of digital twin. Digital twin adoption requires the implementation of various enterprise systems and supply chain solutions, which requires huge investments. Participants argued that organization should select digital tools required to build digital twin capability and partners during the early stages of adoption. Creating awareness and developing clear understanding of the digital supply chain technology is essential for successful transformation.

Interview participant 6 summarized this step as "you have a complete review for your supply chain performance. How are we doing today? How are we going to do? How do you want our supply chain to perform tomorrow? Based on the expected business, expected globalization factors". Therefore, assessment of readiness and current state creates an action plan for digital twin adoption. From the data, it was observed that people involved with consulting or technology solutions are mostly aware of the current state and maturity assessment compared to the practitioners managing supply chain in manufacturing companies. This highlights the fact that manufacturing firms need to learn from external partners regarding maturity assessment, which is the first step in adoption. As indicated in table 1, this step has been moderately supported by data. Only 55% of the interview participants and 47% of the survey participants referenced about the assessment step.

5.1.2 Digitize Supply Chain and Systems Integration

Supply chain digital twin is a digital representation or digital replica of supply chain. Survey participant 12 described supply chain digital twin as "a virtual representation of the end-to-end value chain and it connects across planning systems and execution tools while providing the user community a single engagement level UI with simulation and modeling capabilities".

Developing the digital twin architecture and supply chain cyber physical system involves integration of various systems and data sources in supply chain. The survey participants listed a range of systems for developing the architecture which included: sourcing and purchasing systems, Enterprise Resource Planning (ERP) system, Manufacturing Execution System (MES), Transportation Management Systems (TMS), Sensors and IoT Ecosystem, supply chain monitoring system, digital twins for network modeling and supply chain planning systems.

In addition to the integration of supply chain systems, creation of network modeling digital twin, simulation, and optimization models mimicking supply chain are necessary in this stage. One of the survey participants noted that digital twin consists of "a digital model representing physical supply chain constraints and dynamics in the context of specific decision support problems". Supply chain modeling can be in the form of simulations, optimization, or digital twin systems for supply chain design.

Digital twin displays a single view of all the key components of entire supply chain including mapping of supplier location, mode of transport, lead time, manufacturing machine condition, order status, lot size, mode of distribution, transport capacity, storage, inventory flow, new demands, demand backlog, and demand priority. Some of the participants from interviews called this as 'Supply chain control tower'. By contemplating all the data obtained, a digital twin architecture is developed as shown in figure 3. Most of the supply chain practitioners are aware of various supply chain systems that support digitization strategy. This theme achieved 'high' support from the data with 73% of interview participants and 67% of the survey participants referencing about supply chain digitization architecture. Although most of the participants listed software tools from their functional areas, they lack comprehensive understanding of the list of systems necessary to build end-to-end supply chain digital twin. Only after combining the list of systems suggested by all the participants, a comprehensive list of systems has been identified to develop the architecture.

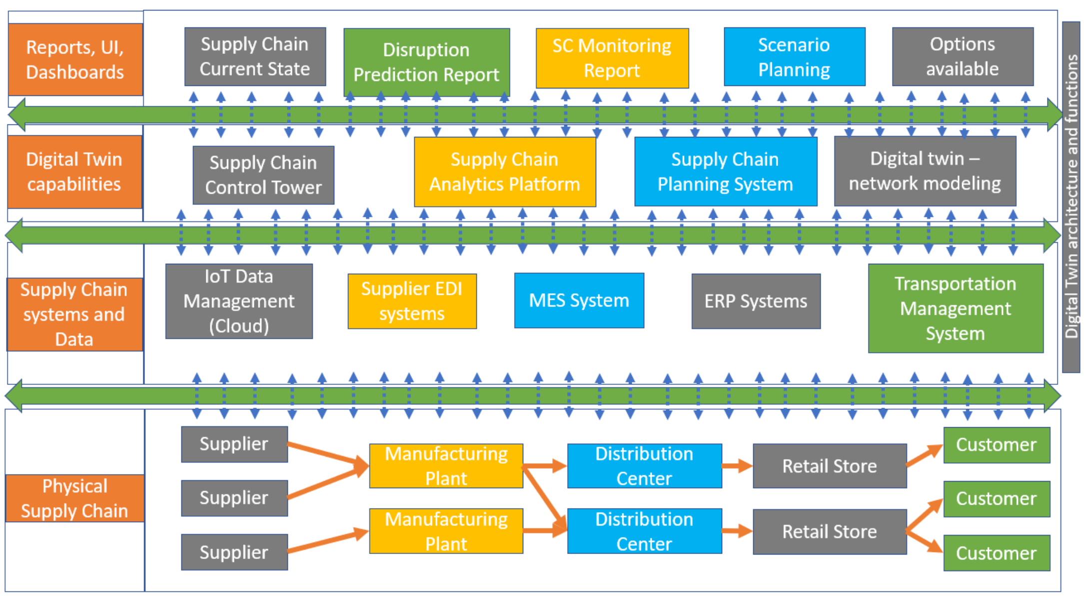

Figure 3. Digital twin architecture

5.1.3 Data Generation, Management, and Value Creation

The participants from survey and interviews argued that organizations begin with pilot projects to realize the value of digital twin before large-scale transformation. Interview participant 2 mentioned "having a bigger road map and promise and then breaking it down to a small pilot to make it happen to show the value and then to scale it step-by-step. This is how, I've practically seen that happen"

Generating data from supply chain and ensuring data quality are important in the early stages of digital twin adoption. Interview participant 5 briefed the importance of data discovery/generation as "we talk about where to source the data? How to secure the data? How to consolidate and enrich the data? Data enrichment is a big deal in a supply chain, global supply chain because everything down the road will depend on the quality of the data, right? So, data enrichment, clean up the data, enrich the data and get data ready for data science". Similarly, organizations need to determine the data management routines for efficient data acquisition and usage. Survey participant 13 talked about the data management aspect as a learning exercise where companies "have to kind of learn to do the get the right sensor, sensor management and all that stuff so."

The next step in the data processing is converting the data gathered into an insight for supply chain disruption management. Interview participant 8 explained, "the second part, we entered phase, what I called as data science and all the solutions on top of the data science itself to be able to what I call contextualize the data. Because as you know, so contextualization as you know, it is data plus domain expertise. Together you put the right data and right context and make it ready for a decision". So, organizations should develop routines for converting data into insights for making decisions during disruption management. Most of the supply chain practitioners are aware of generating data, cleaning, and creating insights from the data which could support in disruption management especially with disruption predictions. This theme achieved 'high' support from the data with 73% of interview participants and 60% of the survey participants referencing about the data collection and data science aspects.

5.1.4 Supply Chain Monitoring and Planning Environment

At the final stage of digital twin adoption, organizations should develop a digital twin that consists of the following capabilities: monitoring of supply chain in real-time, predicting any potential disruptions, and real-time concurrent planning across the supply chain. Once a signal of disruption or disturbance is predicted by the monitoring system, organizations begin the impact analysis in digital twin. Organization uses the analytical platform and planning systems to perform real-time scenario planning. Digital twin aids in adding or removing a supply chain node based on the impact and determining the best option for mitigating the supply chain disruption.

The digital twin enables scenario planning and generate insights on important KPIs. Interview participant 11 described "you can look at a wide variety of hypothetical situations for your supply chain planning environment to understand what would happen. If your factories were shut down due to a pandemic, or what would happen if your supply chain lead times extended? What would happen if you had an unexpected demand spike or an unexpected demand decrease"? By using the analytical and planning platform, organizations can optimize their response and recovery plans for supply chain. Therefore, digital twin enables real-time scenario planning and develop optimization plans for managing supply chain disruptions using real-time data. Most of the supply chain practitioners are planning to build and utilize digital twin as the monitoring and planning environment for managing supply chain disruptions. This theme achieved 'very high' support from the data with 100% of interview participants and 80% of the survey participants referencing about the monitoring and planning environment. Due to recent disruptions and pandemic, supply chain practitioners are looking for digital capabilities that help in supply chain monitoring and planning.

A framework for adopting digital twin and managing supply chain disruptions has been developed and shown in figure 4. The framework outlines the four stages of digital twin adoption discussed in this section.

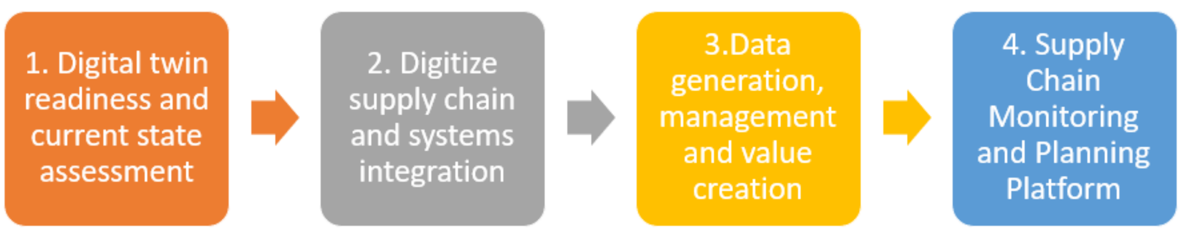

Figure 4. Digital twin adoption phases

5.2 Supply Chain Resilience Capabilities

This section discusses the capabilities built in supply chain through the adoption of digital twin. Both interview and survey participants suggested that digital twin technologies such as IoT enables resilience in supply chain in three major ways – creating real-time visibility, making quick decisions, and executing quicker actions or response to supply chain disruptions as shown in figure 5. Similarly, table 2 shows the level of support available from the data for these resilience capabilities developed by digital twin.

Supply chain digital twin integrates end-to-end supply chain, which enables transparency and real-time information sharing in supply chain. Interview participant 5 highlighted the visibility capability by commenting "you can monitor the whole state of supply chain and understanding that supply chain is under control or simply if you know you have right data feeds and then that should go back to some kind of central analytics which can take all that information and give a real time information of status quo of what's happening and create a prediction if something goes wrong". Therefore, digital twin improves supply chain visibility with high quality real-time data. As shown in table 2, supply chain practitioners are highly aware of the potential of digital twin and are planning to utilize digital twin to create visibility in supply chain. Interview participants indicated real-time visibility as the primary value or capability that companies intend to gain through digital twin. This theme achieved 'very high' support from the data with 100% of interview participants and 87% of the survey participants referencing about supply chain visibility capability.

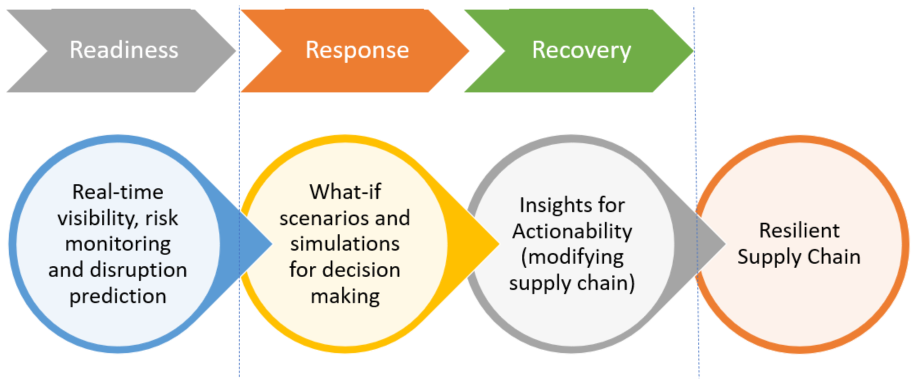

Figure 5. Resilience elements enabled in supply chain by digital twin

Once, supply chain visibility has been achieved, the next step is converting the visibility into supply chain decisions. Digital twin gives "the chance to actually make decisions about what step to take next to give a chance to prepare for how to respond in the face of disruption" as noted by interview participant 3. During the Suez Canal blockage, one of the clients of interview participant 5 used digital twin to develop recovery plans. Interview participant 5 mentioned that the client "can make decisions on well, do I want to potentially pay more to use air? Am I going to wait for this ship to come into port? It was waiting worth the savings of transportation costs. Or do I absolutely need this freight?". Therefore, digital twin offers support in decision making for maintaining continuity in an optimized way. This is accomplished by the capability of digital twin to perform scenario planning and interview participant 2 pointed out that "a digital twin is a simulation, or maybe an emulation of what is going to be happening, and so it has a tremendous amount of value for us to play what-if games". Therefore, digital twin enhances the ability to make quick data-driven decisions during disruptions. Most of the participants highlighted the importance of digital twin as a planning environment to perform scenario planning during disruptions. This theme achieved 'very high' support from the data. As shown in table 2, 91% of interview participants and 73% of the survey participants envision digital twin as a planning environment for disruption management.

Table 2. Resilience capabilities enhanced by digital twin

Resilience capability	**Number of Interviews referenced**	**Number of Surveys referenced**	**Interview referenced percentage**	**Survey referenced percentage**	**Support from data**
Real-time visibility	11	13	100%	87%	Very high
What-if scenarios	10	11	91%	73%	High
Actionability & insights	6	9	55%	60%	Moderate

The final and critical step in the supply chain disruption management is executing quick reconfigurations to adapt to the changing landscape. Interview participants suggested that pre-established routines, simulation drills and orchestrion of resources enables quick response during a disruption. Digital twin provides protocol (optimized response and recovery plan) for all the supply chain members to follow during response and recovery phases. Interview participant 7 argued that "what we can do with the Internet of Things and supply chain analytics is give ourselves some information about the disruption so we can respond quicker and in real time". Digital twin also enables an organization to share information in real time and collaborate with partners as noted by survey participant 14 "we try to be very responsive to them as well and provide visibility into our own needs so that we can communicate very clearly what we're going to need and when given advanced notice". Therefore, digital twin enables the organization to perform optimized supply chain reconfigurations at a faster pace by collaborating with supply chain members in real-time. Most of the supply chain practitioners agree with the role of digital twin in quick reconfigurations and actions implementation during disruption. But this theme has achieved only moderate support from the data with 55%

of interview participants and 60% of the survey participants referencing about supply chain reconfigurations through digital twin, as noted in table 2.

As such, this research determined that supply chain digital twin is a digital replica of a supply chain with monitoring, scenario planning, and analytical capabilities. Supply chain digital twin plays a major role in enabling supply chain resilience and supports in readiness, response, and recovery phases. Supply chain visibility improves readiness in supply chain. Monitoring of supply chain and predicting potential disruptions ahead provides time for organizations to prepare and manage disruptions better. Conducting what-if scenario analysis and planning for response improves the decision-making capability of a company. In addition, digital twin helps in quicker recovery from disruptions, which has been supported by the interview and survey participants.

6. Conclusion, Future Research, and Research Contributions

Supply chains are critical to an organization's revenue and competitive advantage. Adopting digital twin for managing supply chain and navigating disruption is an essential investment for organizations. Matching the digitization strategy with overall firm's business strategy is critical for successful digital transformation (Bär et al., 2018). However, absence of a guidance framework for digital twin implementation limits supply chain leaders in building a business case for digital twin adoption that matches with the overall business strategy.

This research study determined that digital twin adoption can be accomplished in four sequential phases. Organizations should start with evaluating their current supply chain challenges and create use cases for digital twin adoption. Results from this study shows that supply chain leaders lack the awareness of maturity assessment step needed at the initial stage of digital twin adoption. Maturity assessment depicts the areas to improve in supply chain and develops a roadmap for organizations to adopt digital twin. Once the value of digital twin is discovered from pilot projects, firms need to digitize end-to-end supply chain and integrate various supply chain systems to create a real-time supply chain control tower and supply chain planning platform. Such a capability of digital twin enables organizations to monitor supply chain and predict disruptions. Firms can perform what-if scenario analysis and create response plans to recover from disruptions in an efficient manner. Digital twin improves the supply chain visibility which is essential for quick decision making and develop an action plan. Then, organizations utilize the developed plan to reconfigure supply chains and execute network modifications to maintain supply chain continuity, generate revenue, and remain competitive. The digital twin architecture model developed from this research based on empirical data guides manufacturing organizations in the implementation of various enterprise systems and form digital twin architecture that supports in disruption management.

This research developed a framework for digital twin adoption and took an initial step to address the literature gap. As a first step, organizations should develop routines and projects to improve supply chain visibility. Without visibility quick data-driven decisions and action implementation are impossible. Therefore, organization should evaluate their current maturity and improve their maturity level sequentially. The primary objective of adopting digital twin is enabling quick, optimized, data-driven actions to reconfigure supply chain, maintain continuity, and improve organization revenue. Future research works can investigate digital twin adoption framework using various research methods such as full-scale survey, case studies, and Delphi technique. Research efforts in the aforementioned directions will validate the results of this research study.

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