Enhance Supply Chain Resilience through Industry 4.0 – A view of designing simulation scenarios

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***Abstract*— COVID-19 pandemic and the Ukraine war demonstrate the inevitability of supply chain disruptions. A lack of effective supply chain resilience (SCR) causes mismatches between demand and supply, and the destabilization of normal operational policies in production, distribution, and inventory control. Existing research mainly provides different definitions and measurements of supply chain resilience for different product supply chains. In this paper, we look at how Industry 4.0 (I4.0) technologies enhance supply chain resilience. An I4.0 enabled architecture is designed for a factory with multiple suppliers and extended inventory for improving SCR. Different simulation scenarios for a LED factory are designed for demonstrating I4.0 technologies supporting SCR in different phases.**

***Keywords*— supply chain resilience, industry 4.0, supply chain disruption, supply chain recovery, simulation.**

I. Introduction

COVID-19 pandemic and the Ukraine war demonstrate the inevitability of supply chain disruptions. A lack of effective supply chain resilience (SCR) causes mismatches between demand and supply, and the destabilization of normal operational policies in production, distribution, and inventory control. All leading to financial losses. SCR is critically important to both organizations and society. Existing research mainly provides different definitions and measurements of supply chain resilience for different product supply chains. How Industry 4.0 (I4.0) technologies support supply chain resilience (SCR) at strategic, tactical, and operational levels is still missing. Industry 4.0 shows promising possibilities to mitigate supply chain risks and enhance SCR.

Spieske and Birkel investigate how different technologies for Industry 4.0 (I4.0) improved SCR in [1]. The paper discusses different I4.0 enabler technologies which can potentially support SCR. The study further looks at how the various I4.0 technologies can benefit the SCR antecedents, such as agility, supply chain (re-) engineering, supply chain collaboration, and established SCR management culture in all SCR phases. The research emphasizes how the I4.0 technologies enhance SCR during a pandemic in different phases, i.e., pre-disruption, response, recovery, and achieving superior supply chain performance compared to the pre-disruption state. The paper analyses the potential benefits of I4.0 for enhancing SCR without providing an application for a specific supply chain.

Belhadi et. al. review manufacturing (automobile) and service (airline) supply chain resilience to the COVID-19 outbreak [2]. In this paper, two research questions are answered, i.e., what is the level of resilience of manufacturing and service supply chains against the COVID-19 outbreak? and what are the short and long-term risk mitigation response strategies to manage COVID-19 disruptions in developing resilient supply chains? A mixed-method research approach is employed, using a combination of both qualitative and quantitative methodologies. The research focuses on two specific supply chains, the automobile and airline supply chains, but no I4.0 enhancing SCRs are explored.

Wieland and Durach investigate the definition of SCR from engineering and social-ecological perspectives [3]. The two metrics to quantify supply chain resilience are time-to-recovery (TTR) and time-to-survive (TTS). Financial Impact (FI) is another factor to measure SCR. FI quantifies SCR using total induced cost under different aspects, such as profit, revenue, sales, transportation, and inventory costs [3], [4]. The proposed measurements of SCR are useful for analyzing SCR. However, the research does not provide a predictive or prescriptive SCR analysis.

In this paper, Section II categorizes different I4.0 technologies for SCR. We look at how I4.0 technologies support SCR soft enablers in Section III. An I4.0 enabled architecture is designed for a factory with multiple suppliers and extended inventory in Section IV. Different simulation scenarios for a LED factory are designed for demonstrating I4.0 technologies supporting SCR in different phases in Section V. Finally, Section VI concludes the study.

II. I4.0 enabled Supply Chain Resilience

The concept of Industry 4.0 (I4.0) has gained popularity and its digitalization aspects can be harnessed in a diverse range of production systems, manufacturing systems, and Supply Chains (SCs). I4.0 and its enabling technologies bring about several opportunities in mitigating risks, increased transparency, complexity management, and increased flexibility across organizations. These technologies include Internet of Things (IoT), Cyber Physical System (CPS), Artificial Intelligence (AI), Blockchain, cloud computing, Big Data Analytics (BDA). Given the various I4.0 technological enablers, the question remains how specific I4.0 technologies can enhance Supply Chain Resilience (SCR). The answer depends on the specific SCs for different industry sectors. Some studies only consider I4.0 technologies such as IoT and CPS in SCs for manufacturing and productions [5, 6]. In contrast, other studies include various digital technologies like AI, Blockchain, cloud computing, CPS, IoT, BDA [7], Robotics [8] and Addictive Manufacturing [1].

Using I4.0 technologies will help an SC deal with unknown disruptions, and proactively avoid any future occurrences [2, 6]. However, different SCs' purposes, i.e., production, manufacturing, or services for different industrial sectors may require different configurations of the above-mentioned I4.0 technologies for enhancing their SCR. Additionally, the connection between I4.0 technological enablers and SCR enablers is still unclear. Before mapping between I4.0 technical enablers and SCR soft enablers, we briefly explained each of the I4.0 technologies and their enhancements in SCs depicted in Table I. The table consists of the eight identified I4.0 enablers, their related technologies, as well as how these technologies could support SCs.

TABLE I. I4.0 TECHNOLOGIES AND ENHANCING SUPPLY CHAIN

Technologies	Related technology	Supporting SCs
Cloud computing	Big data analytics, IoT, CPSs	Enhance SC performance and connect data with a digital thread across the value chain. It also helps with risk mitigation, resource efficiency, and regulatory compliance.
IoT	IoT, AI, Big data analytics, CPS	Monitoring the entire SC. Improving the supply chain process, risk knowledge, and risk strategies. The capabilities of IoT capture the connectedness and control needed across the SSCs. This capability helps SCs to adapt and be prepared in case of any disruptions.
Big data analytics	BDA+ simulation = Digital twin	BDA supports SCs as a core element of future I4.0 SCRES initiatives. • Predicting risk events, proactive response planning, and • reactive real-time control, • continuity plans in times of SC disruptions • SC digital twins
AI	AI, BDA	large datasets, decision-making, prediction, and learning
Cyber physic systems (CPSs)	Cloud computing BDA, AI, IoT	An automated system for *detecting and transporting testing samples from the assembly line* to a laboratory mitigates potential quality risks more reliably and efficiently than human workers ever could.
Additive manufacturing (AM)	Cloud computing, BDA, AI, IoT	Reducing potential risk sources in SCs.
Block Chain (BC)	Cloud computing	SCs can significantly benefit from these application areas since BC's "super audit trails" improve open communication, coordination, and trust across company boundaries, i.e., SC collaboration/governance.
Robotics	IoT, AI	An autonomous robot can help to perform tasks with little or no human interaction. The robot is programmed with AI to learn and recognize things in its immediate environment. Consequently, improve the speed and accuracy of routine operations, lower the error rate, reduce the frequency of inventory checks, decrease costs, and improve data collection.

III. MAPPING BETWEEN I4.0 TECHNICAL ENABLERS AND SCR SOFT ENABLERS

Supply Chain Resilience is achieved through actions taken to prepare for or react to disruptions in SCs due to the incapability of traditional risk management. Pro-active building of resilience has proven to be an effective strategy to help SCs react, respond, cope, and recover from continuous events that cause disruption. The literature identifies several essential SCR (soft) enablers and their dimensions from multiple perspectives i.e., based on different industry and country contexts [9]. This includes flexibility [10], culture [11], capacity [12], collaboration [13], SC re-engineering, agility, collaboration, knowledge management [14] and risk management culture [15]. Spieske and Birkel [1] build upon the work of Christopher and Peck [15] identifying visibility, velocity, culture, collaboration, sources, SC understanding, and SC design as key enablers for SC resilience. In this paper, besides looking at I4.0 technical SCR enablers, we also look at soft SCR enablers and their relations with I4.0 technologies enablers in enhancing SC resilience. These relations are summarized in Table II.

TABLE II. RELATIONS BETWEEN SOFT SCR ENABLERS AND I4.0 ENABLERS

Soft SCR Enablers	Mapping between I4.0 and SCR Enablers	I4.0 Techno-logical Enabler
Flexibility	This involves the ability to reconfigure supply chains or adapt to changes as required with minimum time and effort. With increased connectivity and integration supported by IoT, processes, systems, and products become more easily reconfigurable. There is also improvement in product quality, product delivery, and overall performance. BDA also enables testing alternate solutions using simulation and optimization tools.	IoT, AM, BDA, Robotics
Culture	An organization needs top management support and a risk-aware mindset. With industry 4.0, top management could be able to interpret insights from processed data using BDA.	BDA, CPS, AI, IoT
Collaboration	Collaboration is one of the key elements of SCRs. Interoperability enables one or more organizations to cooperate, plan, and execute SC operations effectively. This allows them to achieve a shared goal, e.g., data collected from IoT devices reduces unexpected results among partners.	IoT, Blockchain, Cloud computing,
Agility	This involves the ability to respond to unpredictable events on time. It can be achieved through a rapid change to business processes and systems using data collected in real time.	BDA, cloud computing, IoT
Visibility	Monitoring SC processes enables visibility into allocating and prioritizing resources, e.g., tracking inventory. With I4.0 technological enablers such as BDA, market visibility and information can be shared and improved in real time using predictive analytic techniques. This increases confidence in SC whereby risks are minimized due to effective response. It can increase productivity, improve customer satisfaction, and improve data quality.	Cloud computing, IoT, BDA, AI, CPS, block chain
Reduction of uncertainty	IoT gives SCs the ability to complete tasks and recover from disruptions rapidly by efficiently utilizing the information collected and modelled. It helps to reduce costs, complexity, and inaccuracies along the supply chain. With BDA, early warning signs are provided, situations are evaluated using external data, and proactive actions are taken.	IoT, BDA

Re-engineering	SC re-engineering provides an opportunity to reduce the impact of disruptions as and when they occur. This could be achieved by making sure that the SC strategies chosen could keep several options open in responding to any disruption. I4.0 technologies can help organizations rethink and redesign their SC strategies to cope with resilient and robust processes.	BDA, IoT, Cloud computing
Integration	SC partners integrate to share valuable information about the latest markets, products, customers, and potential markets. Implementing IT integration provides real-time and fast response times to disruptions.	Cloud computing, IoT, BDA, AI, CPS,
Capacity	This is the ability or capacity of SCs to adapt to change and grow when faced with unexpected turbulence, while at the same time retaining the system's basic function and structure.	BDA, IoT, Cloud computi
Knowledge Management	KM has been identified as one of the strategies used to optimize SCs operations through knowledge sharing. This helps to better understand disruptions by having enhanced visibility, flexibility, and velocity in the supply chains and in turn increases SCR. I4.0 technologies like AI and BDA give SCs the ability to collect and create organizational knowledge or use cloud computing to disseminate knowledge..	AI, BDA, cloud computing

We conceptualize SC resilience enablers and their relationship with I4.0 technological enablers based on pro-active and reactive resilience strategies as described in the literature (see Table 3). The proactive strategy involves the actions or processes taken by SCs to anticipate, prepare for, or control disruption rather than responding to it after it has already occurred. Being pro-active for any SCs requires the ability to easily identify early warning signals as well as monitor deviation at the earliest stage. This will prevent potential disruptions or mitigate their impact. The proactive strategy includes preparation, anticipation, prevention, and readiness. On the other hand, reactive strategies involve responding and recovering from disruptions and then returning to normal business operations and possibly growing them in good time. The reactive capability includes the ability to respond, recover, return, and grow i.e., maintain the continuity of business operations. Both strategies are linked through the readiness aspect of the proactive strategy.

With I4.0, in the proactive stage, technology like BDA could be used to build a realistic disruption scenario based on different types of data. And in the reactive stage, BDA could be used to identify disruption in real-time, which in turn provides the best way to respond and recover from disruption in an acceptable time. For instance, the real-time disruption data could be fed into a reactive simulation model for recovery policy simulation and optimisation (See Section 5 for details about simulation scenarios and I4.0 technologies based on proactive and reactive strategies).

IV. SUPPORTING I4.0 ENABLED SCR ARCHITECTURE

A supply chain can be embedded in the context of a broader industrial ecosystem with supporting IT architecture. Such an architecture is ideally based upon a firm, existing, basis such as provided by FIWARE, an open-source framework for Industry 4.0 as well as a service ecosystem composed of various components [17]. FIWARE offers adapters for enabling access from different IoT/smart devices, components, and services to big data analysis components for the development of different application solutions. Interoperability and modularity are the key aspects that the FIWARE platform promotes and supports. The I4.0 enable FIWARE architecture offers SCs and manufacturers flexibility, interoperability, big data analytics, and the easy integration of different IoT smart devices.

Starting from the basis of FIWARE Fig. Figure 1 illustrates an I4.0-enabled SCR architecture for a manufacturer. In this architecture, manufacturers can gather industrial data from different machines, IoTs, etc., supply chain data crossing multiple organizations, as well as general news of different regions for monitoring the supply chain and updating regulations.

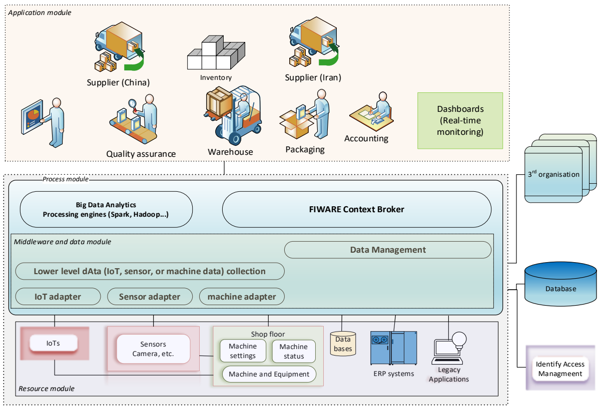

Fig. 1. I4.0 enabled SCR architecture

On the basis of our previous work [18, 19, 20], the architecture is organized into three levels: resource, process, and application. Sensors, IoTs, items on the shop floor, and legacy systems are located at the *resource level*. IoT systems embedded in the supply chain track some critical data for SCR. Different adapters for sensors, IoTs (from transportation or supply chain-related monitoring), and machines are used for data collection and managed at the middleware and data modules at the process level.

The *process level* includes big data analytics and processing engines as well as the FIWARE context broker. The FIWARE context broker provides the communication mechanism with different adapters and the related data sources and storage required for the platform. The data analysis and simulation related to the supply chain are processed at the process level. The existing data process modules (as services) can be reused with consideration of both manufacturing data and supply chain data. The newer suppliers' data can be added through the adoption of new IoT systems or the legacy supply chain management system of the newer suppliers.

At the *application level*, different applications will be deployed for different stakeholders for monitoring, tracing, simulation, or decision-making purposes. This provides an integrated system that supports the stakeholders in the supply chain for making the process efficient and effective while retaining the flexibility inherent to this lean approach.

V. VALIDATING I4.0 ENABLE SCRS USING SIMULATION SCENARIOS

To validate the integration of Industry 4.0 technologies for enhanced supply chain resilience we use a supply chain example from [21]. We also simulate various disruption scenarios for this supply chain. The supply chain consists of three main parts: Supplier (foreign), Manufacturing Site, and Customer. Raw Materials (parts) for an LED panel are imported from a supplier in China and assembled at a local manufacturing site in Iran and shipped to customers in different parts of the country. Five simulation scenarios are designed to reflect the different phases of SCD in the mentioned supply chain, i.e. before SCD, during SCD, and after SCD.

I4.0 technologies are not yet part of the supply chain. Without applying I4.0 technologies, backup inventory and redundant local suppliers are considered for recovery in case of an SC disruption. For each scenario, we look at which I4.0 technologies could improve SCRs from the perspective of the various resilience strategies such as proactive strategy and reactive strategy. The integration of I4.0 technologies with simulation in different scenarios presents challenges related to scalability and real-time analytics. Commercial software packages like Anylogistix have inherent limitations for real-time simulations and integration with other simulators (needed to model complex multi-party supply chains where steps are not conditionally independent). The proposed scenarios will be simulated using an I4.0-enabled framework (see Section 4) with multiple data sources. This supports scalability and efficient integration beyond existing supply chain simulation tools, such as Anylogistix.

A. *Disruption free scenario (scenario1)*

In the base disruption-free scenario, the supply chain works in a normal way. The supply comes from a foreign supplier in China, no local supplier is used, and the manufacturing site is operating normally. According to the original design, the supply chain can reach its optimal capacity. However, the general fluctuations in international transportation costs, raw material prices, regional economical situations, and product demand still impact the profits of supply chain owners, the SC related stakeholders, and the manufacturer. I4.0 technologies provide a unique opportunity to further optimize supply chains, including improving supply chain resilience at reduced overhead costs.

Section 3.1 identified eight I4.0 technologies as SCR enablers. We classify these technologies into two categories: essential and further enhancement in Table III. Without the essential technologies the potential for supply chain resilience is significantly impaired.

TABLE III. RELATION BETWEEN I4.0 TECHNOLOGIES AND SCR WITHIN SCENARIO 1

	I4.0 technology	Enhance SCR
Essential	Cloud computing	Ensure that supply chain information and integration remain available throughout disruptions or increased demand.
	IoT	Tracking SC information and/or production information
	Big data analytics	Simulations based on the multiple sources Analysing data from multiple sources to gain deeper SC insights (enabling optimization, pre-emptive handling of disruptions etc.)
Further enhancement	AI	Predictive or prescriptive SCR
	Block Chain	Trusted SC and improve trackability of SCR
	Cyber physical systems	Optimising demanding, production and SC for Supporting SCRs
	Robotics	Automating production and SC for supporting SCRs

Simulation in the disruption free scenario can provide the behavioural data that can then be used to provide a baseline for the prediction and evaluation of parameters like consumer behaviour, optimal performance of manufacturing and growth possibilities etc. When combined with real-time data such as collected by IoT devices, the baseline simulation allows for the detection of deviations from expectations, and as such allows for earlier reaction to interrupting events thereby reducing their impact.

The use of base-line simulation in combination with real-time data can also play a significant role in the recovery phase where a return to normal needs to be managed in a way that optimizes costs, resilience and speed. The simulation can highlight optimal inventory levels, performance overheads and potential issues (especially in systemic cases such as the COVID-19 pandemic where the recovery needs to take into account the full system).

As there are no disruptions in this case, handling the supply chain from the perspective of a cyber-physical system can also play a vital role in realizing better performance and resilience. Integration of physical technologies (intelligent machines, intelligent infrastructure etc.) and digital technologies (Information Systems, Monitoring and Analysis technologies etc.) can help in identifying key areas where the supply chain needs improvement and enhance resilience strategies, as well as enhance the modelling, monitoring and simulation of the system overall.

Blockchain technologies can help handling the multi-party nature of the supply chain in a way where trust can be minimized. The distributed nature keeps the system resilience to failure of counterparties. In cases where traditional enforcement mechanisms are not optimal approaches such as smart contracts can allow for an alternative way to create, record and enforce contracts.

Simulating disruption-free requires data from all parts of the supply chain. Customer behavior (*demand patterns, product quantity, product ID*), real-time data from IoT devices at manufacturing sites (*machine ID, resource utilization, down time*), tracking data from blockchain network throughout the supply chain, especially from the supplier side, and updated analytics on orders. It resembles the information that is likely available in a real-world scenario and therefore provides a baseline from which supply chain resilience is normally achieved and measured.

B. *Disruption with local backup supplier (scenario2)*

After discussing the disruption free scenario, the scenario with a local backup supplier scenario is an example of a reactive SCR strategy. Simply adding a local backup supplier can improve the SC performance and enhance the SCR without the application of I4.0 technologies. Based upon the scenario we also identify places where I4.0 technologies would enhance SCR and present possible opportunities for improving the performance of the SC.

I4.0 technologies can be applied to both the supply chain and the local backup supplier's manufacturing processes. The general relation between I4.0 enablers and enhanced SCR of the supply chain in Table 1 remains. The local backup supplier should be included in the cloud systems that make all relevant supply information are available for analysis and integration by the stakeholders of the SC. IoT can be applied to part/ product/material delivery. This provides a SC data source for the big data analytics of the whole supply chain. If some special multi-party collaborations are involved, blockchain technology can also be applied to the local backup supplier. I4.0 technologies such as CPS and robotics depend on the nature of the supplier. CPS and Robotics can apply to the manufacturing sector, but they are too expensive for most smaller manufacturers. As a backup supplier, the local manufacture can be reluctant to invest on.

The focus of data for simulation in this scenario is the ability of the local supplier to meet demands of the manufacturing site. Transportation data (*Transportation Time*), data on routes (*Route Aa, Route B etc*.), cost of transportation, number of products/materials, real-time data from IoT devices to track the supply chain (*Timestamp, Time to destination*) as well as requirements from manufacturing site (e.g *order quantity*) are all involved in this scenario.

C. Disruption with reduction manufacturing capacity (scenario 3)

Disruptive events such as COVID-19, have an impact on the manufacturing site where human resources (people) work for various manufacturing and logistic tasks. Social distancing measures or illness from the virus are some of the factors that needs to be considered while looking at impact of disruption on the overall supply chain. Moreover, if a machine at the manufacturing site malfunctions, its repair could also be affected because of non-availability of personnel or tools/parts that need to be replaced cannot be imported due to COVID-19 restrictions. In this scenario, we develop reactive strategies to mitigate the disruption impact and also propose proactive strategies that can be adopted to avoid such an impact. .

One reactive strategy for SCR when manufacturing capacity is reduced, is to use real-time data (*machine performance, machine utilization, number of staff available, staff resource utilization*) to help in identifying critical areas for improvement and careful management leading to improved supply chain performance. The data provides valuable insights regarding the current state of the manufacturing site. Dynamic simulation models using this data and what-if scenarios using different resource utilization parameters can help in identifying the critical areas where more improvements are needed. Hence, better recovery time is achieved and SCR is enhanced.

A proactive way to make supply chain more resilient is to simulate and predict the performance of a manufacturing site in cases of disruption and make sufficient resources available beforehand. This adaptation comes at a significant financial cost and for any disruption the prediction (and adaptation) is likely to be inaccurate. Hence, I4.0 technologies and in particular (near) real time disruption data (*machine capacity utilization, performance of machines etc*.), advanced analytics and what-if simulations based on the performance of supply chain presents an attractive solution to enhance supply chain resilience in case of disruption as significant as COVID-19.

Data items used in this scenario constitute of requirements from manufacturing site. For example, data related to product requirements sent to supplier (e.g *order quantity, product type etc*.), resource utilization and possible requirements of resources to achieve optimal performance (e.g *number of people and machines in working, capacity utilization, resources deficit etc*.). The real-time data for machine performance (*machine ID, products assembled/hour, machine utilization(%) etc*.) is also used to monitor the machine and whether or not any repairs are needed or predictive maintenance measures needed or not.

D. Disruption with backup inventory (scenario 4)

In this scenario, we use backup inventory as a resilience strategy instead of a local supplier. This strategy is used as a proactive measure. We assume in this scenario that we do not have a local supplier available and complete reliance of service delivery is on the back up inventory. In case of backup inventory as a proactive strategy, estimated inventory for products is maintained and when the disruption occurs, this inventory is exhausted until alternate means of procurement are arranged.

Use of historical data for inventory maintenance and real-time simulations can help in building scenarios for variable inventory usages. This can help in building an optimal inventory which helps in avoiding the extra financial costs in the above-described cases. Real-time data from IoT devices (such as *products usage, inventory utilisation*) and supply chain tracing can also help build supply chain twins at multiple disruption levels during different phases of the pandemic. This can help massively in building supply chain resilience and help reduce recovery time and presents exciting opportunities for immense growth by making decisions based on these innovative scenarios.

For this scenario, the data points used are from inventory for each type of product (*product ID, product type, quantity*), traceability data from private blockchain (*route, time elapsed for transportation, delay etc*.), real-time inventory usage data and historical data of inventory utilization. This data provides strong basis for dynamic simulations which are used to make efficient decisions for supply chain resilience during and after the disruption.

E. Disruption with consumer demanding changes (scenario 5)

The final scenario that we consider for simulation to enhance supply chain resilience is one in which consumer demand patterns are considered proactively and reactively. When the COVID-19 pandemic started, there was a significant reduction in demands for various products like clothing and travel related products. On the other hand, demand for hygiene products surged manyfold. It is imperative to consider consumer demand changes during a disruption as huge as COVID-19 pandemic when modelling supply chain resilience.

There are two cases that we can consider using I4.0 technologies for better and more resilient supply chain decision making. Data related to consumer demand patterns before the disruption and simulating increase and decrease in consumer demands can be simulated to predict an estimation of demand patterns throughout the supply chain. This can be done proactively, before the disruption occurs. However, when the disruption occurs, we can build dynamic simulations based on updated data regarding demand patterns. These dynamic simulation models can be used to make decisions regarding changes in supply chain for example demand for specific product or raw material. This can consequently enhance the supply chain resilience in latter stages of disruption and can make the recovery process robust. The comprehensive data on consumer demands present immense growth possibilities after the recovery of the supply chain and strengthens future resilience due to the more precise models.

To simulate the impact of disruption on consumer demand and the resultant impact on the overall supply chain resilience, historical data for consumer demands (*order quantity,* *customer ID, product ID etc.*), real-time data of consumer orders pattern (*order ID, product ID, customer ID* (12 hours), data from manufacturing site (*products received, quantity, product ID etc.*) are used. This data provides meaningful insights from simulation to prepare a reaction to the disruption and make the supply chain more resilient to future disruptions.

All the above-described simulation scenarios can be combined to develop a supply chain twin which uses data from different scenarios and simulate all aspects of the supply chain and make each part of the SC more resilient in case of disruption. Using I4.0 technologies like dynamic and predictive simulations, decision support, real-time data from IoTs and interactive dashboards using cloud solutions can pave the way for a comprehensive solution for supply chains and prepare the supply chains for higher order disruptions in the future.

The integration of I4.0 technologies and supply chains in context of industry 4.0 increases complexity and simulation of such a supply chain become more complex. Traditional simulation software packages like Anylogistix have inherent limitations when simulating such dynamic supply chains. Real-time data from IoTs in conjunction with change in disruption levels and dynamic evolution of simulation models makes the traditional commercial simulation approaches insufficient. Therefore, we propose the use of service-oriented simulation framework (see section 4) with comprehensive simulation scenarios to simulate complex supply chains that enhance supply chain resilience for better recovery. We developed different simulation scenarios to model the behavior of supply chain at different levels of disruption. These scenarios integrate I4.0 technologies to model real-time operations of a supply chain and we also show how different I4.0 technologies can help in implementing different types of SCR strategies (proactive and reactive).

VI. Conclusions

In this paper, we identified how different I4.0 technologies support Supply Chain Resilience. We discuss the SCR soft enables related to these different I4.0 technologies. An I4.0 enabled architecture is proposed for a factory with multiple suppliers and inventory. Finally, 5 different simulation scenarios for a LED factory have been presented to demonstrate I4.0 technologies supporting SCR in different phases. The I4.0 enabled SCR architecture allows the sharing of data collected from manufacturing and the supply chain, involving the need to manage data sharing as well as data analysis for supply chain management in different situations.

Our future work will implement the simulation scenarios using different SCR measurements and provide supply chain management for managing potential risks and enhancing the resilience of the supply chain by providing real-time supply chain monitoring, and pro-active and reactive decisions through predictive and prescriptive analysis.

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