Adaptive Risk Mitigation and Supply Network Reconfiguration: AI-Driven Resilience Frameworks for Revitalising U.S. Manufacturing Supply Chains

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1. Introduction, Decreasing global market demands due to excess capacities from different countries and the novel coronavirus (COVID-19) pandemic have reshaped the face of world commercial competition. U.S. revitalization has become increasingly important due to the shifting international market. The U.S. has established a strong foundation in scientific research and maintenance technology, driving movement in the Service-Dominant Logic (SDL). The recovery of the U.S. physical value building system (PVBS) will also require strengthening its physical value building chain (PVBC) or supply chain system. Thus, the United States needs a comprehensive, long-term supply chain component, but current systems are incapable of dealing with the dynamics of PVBC demands and values. This study generalizes insights, designs support and innovative cyber-infrastructure systems, encapsulating material and product requirements and services into a value-added PVBC. Therefore, it may be possible to use these systems to absorb excess country capacities, meet their changing demands, and enhance the resiliency of the U.S. PVBS.

To design a computer-based and controlled systems (CB&CS) component, AI/PD can be used to model behavior of intelligent and nonintelligent systems. AI-powered remote sensors (e.g., ultrasound and modulated light reflections) monitor elements (such as titanium plates) in a flexible sand system. Timer AI-DRIVEN SUPPLY chain resilience for revitalizing U.S. MANUFACTURING 3 controls and remote operation are used to manage the manufacturing process to form blast casings. When magnetic focused MRI is examined and used to control the particle formation production process, pCi. AI-DRIVEN SUPPLY chain resilience for revitalizing U.S. MANUFACTURING 15 It is an issue that affects the readiness for use, maintainability, and sustainability of the U.S. energy infrastructure to handle many value-changes during its life cycle.

1.1. Background and Significance

Resilience is the introduction of scientific theories, concepts, methods, and technical means to restore and quickly reconstruct the disrupted or damaged supply chain and enterprise systems. Resilience is to establish the ability of an enterprise to achieve a constant state of supply to the greatest extent after its supply chain is destroyed or damaged. This article conducts in-depth research on the resilience of supply chain systems using artificial intelligence techniques. This work focuses on the constructs of resilience, research perspective of supply chain systems' resilience, the development experience of resilience based on artificial intelligence, application development, and scientific and technological achievements due to resilience. In addition, the scholarly contributions of this article are also constructed, as well as the innovation and application value and the significant role of the development and application of resilience of supply chain systems.

In 2016, efforts began at the White House to push domestic manufacturing in the United States. However, given the increasing complexity of global supply chains in recent years, supply chains are exposed to various uncertainties and risks, thus affecting the operation of the entire supply chain. In the context of the move toward global manufacturing, supply chain resilience (SCR) will be the foundation for building a "self-rescuer" for U.S. Manufacturing, and the scientific design of advanced systems can achieve by design self-recovery, self-reconfiguration, and self-learning. The resilience of a supply chain is an urgent task for U.S. Manufacturing in today's commercial environment, because even a small process downtime can lead to a huge economic loss. Therefore, it is urgent to study artificial intelligence-driven SCR. In addition, the study of artificial intelligence-driven SCR can promote the establishment of an advanced database and operational ability of an enterprise system to realize the digitalization of enterprise intelligence.

1.2. Research Objectives

The specific aims and objectives of the proposed research consist of three projects, including: 1) To develop a novel AI-driven SCIR approach for improving U.S. manufacturing capability and building resilience in turbulent times. 2) To design holistic methods to NSA and LMD sensors in DDR for strain, vibration, and surface condition monitoring. 3) To develop multipurpose application modules for the proposed SCIR and NSA & LMD sensor system.

Figure 1 shows the workflow of the industrial components of the project. For each aim, we summarize the key tasks. The proposed research projects are designed with the following specific objectives: • To develop a fully integrated, optimal, end-to-end approach for analyzing and matching supply chain disruptions with digital manufacturing and materials design, to improve U.S. manufacturing competitiveness and resiliency. ○ Aim 1 Subproject A: Design a SCIR methodology incorporating NCAM's signature areas such as large area flexible electronics, cyber & AI, mxLMs, and advanced manufacturing principles. ○ Aim 2 Subproject B: Develop an intelligent monitoring and diagnostic tool using NSA in forced vibration for inertia-based measurement and fluid load estimation in advanced manufacturing. ○ Aim 3 Subproject B: Construct and characterize the small strain, wide bandwidth capability of an ultra-low power LMD. • Propose clear application pathways following four technology readiness levels (TRLs) for both the AI-driven SCIR and complete, end-to-end NSA & LMD sensing systems.

1.3. Structure of the Work

This chapter "Introduction" provides an overview of the work, the insights contributed, and a wide-ranging summary of the topics and discussions presented throughout the report as shown in Fig. 1. The key concepts are explained briefly at the end of the chapter. This chapter is organized as follows: Introduction to the field of research is provided in Section 1. The structure of the report is described in Section 1.3. Finally, key concepts are synthesized in 1.4.

This study is conducted under the scopes and research conducted by the Reshoring American Jobs Applied Research (RAJAR) program, a program funded jointly by the U.S. National Institute of Standards and Technology (NIST) and the U.S. Department of Defense (DoD). The goal of this study is to provide an AI-driven supply chain resilience approach for U.S. manufacturers to achieve enhanced operational readiness under new manufacturing paradigms. The U.S. manufacturing industry experienced severe disruption during the COVID-19 pandemic, and AI-driven supply chain resilience solutions are sought to assist manufacturers and supply chain participants to revive and operate their businesses resiliently in a VUCA2 (volatile, uncertain, complex, and ambiguous) environment. As such, the focus is on centralized manufacturing with extensive two-tier supply chains. The approach and methods are, however, generic and scalable to other scenarios and supply chain complexities. Section 1.2 provides an overview of the key insights contributed by our research. In addition to the main report, our journey also resulted in several side reports such as training material for distributed AI applications and a taxonomy of supply chain risk management techniques.

2. Foundations of Supply Chain Resilience

Supply chain management has long been concerned with achieving different types of supply chain performance, such as achieving high service levels, delivering in a timely manner, minimizing costs, ensuring product quality, and more. Yet, more and more managers and scholars are becoming interested in resilience, as they face frequent supply chain disruptions caused by extreme weather-related disasters, geopolitical conflicts, the rise of protectionism, geopolitical tensions, economic nationalism, and electronic and cyber risks. However, there is no standard definition for supply chain resilience, and there is rapidly growing work from several academic communities making it difficult to define supply chain resilience. Generally speaking, the fields under study are operations, information systems, finance, economics, marketing, and computer science.

To ensure an understanding of the manner in which resilience could be nurtured in supply chain management, scholars and managers propose to view resilience as comprising several elements. At the heart of the discussions on supply chain resilience is the question of how to recover and get things up and running quickly, in the aftermath of or during a disruption. But speed is but one dimension; operational resilience is another. Covin and Ferrari (2015) conceptualize operational resilience as the readiness or ability of an organization's operations to cope with disruptions or an unexpected event and to return to normal operation with high productivity in a short time. More recently, Akter et al. (2018) offered a critical theory of resilience in supply chain management, based on a document analysis of resilience definitions. They draw upon several definitions of resilience from fields as disparate as psychology and engineering, in addition to operational resilience noted by Covin and Ferrari (2015).

2.1. Conceptual Frameworks

As has been argued only recently, due to their ability to leverage big data analytics (BDA) in a dynamic, real-time mode, artificial intelligence (AI) and machine learning in particular have become a key supply chain resilience enabler. Using the power of AI and high-performance computing (HPC), this part of the paper introduces novel concepts, theoretical frameworks, and practical solutions. These are the first in their class, as far as the authors know. Possible extensions and dedicated applications in any sector are discussed. These solutions and applications are designed to overcome critical shortages imposed by static, detective, recovery, and prescriptive-oriented isolated theoretical and conceptual developments that center on minor bespoke practical applications of IoT in logistics and supply chains.

This part of the paper and its following sections are based on the application of a range of AI/ML techniques and models. In the first instance, we refer to 'wide and deep' feedforward neural networks that simultaneously build feature vectors and exploit training data from dissimilar sources, cloud computing and data fusion for deep neural network (DNN) ensemble-based model training, and principled methods for robust DNN output prediction. We also apply reconstructed reliability diagrams in the intersection of AI and change detection for anomaly detection, anomaly localization, and, as in this context, the characterization of system-state anomalies, as a necessary conceptual prerequisite for autonomous responses. The successive application of BDA/IoT, AI, and HPC ensures the delivery of each of the aforementioned functionalities of supply chain resilience and conjugates into a supply chain end-to-end cyber resilience lifecycle management. This rests on theoretical foundations, conceptual frameworks, and computational models that are informally introduced in Section 2, ensuring the rigor of bio-inspired system-state modeling combined with AI-inspired bioinformatics.

2.2. Key Components of Resilience

Supply chain resilience is essential for businesses striving to ensure the continuity of their business operations and avoid costly disruptions. Typical examples of disruptions include natural disasters, infrastructure problems (e.g., power outages), operations breakdowns in parts suppliers, and transportation disruptions. To address supply chain-related issues, resilience approaches are attracted to the manufacturing sector; compared to the service sector, manufacturers are expected to have higher gains from supply chain resilience and long-term innovation. Alternative models for supply chain resilience and energy management include the use of technologies such as cyber-physical systems and artificial intelligence (AI) techniques to improve resilience, thus saving on energy and production costs. In the present manuscript, we chiefly focus on the U.S. manufacturing industry.

When evaluating promising candidates for resilient supply chains, we must first distinguish between factors fostering resilience properties (such as agility, flexibility, adaptability, etc.) and resilience itself. We observe that the factors of supply chain resilience may be catalogued as follows: First, reducing opaqueness and asymmetry information; second, diversify; and finally, a fast reaction. This working ratio and the total redistribution time typically fluctuate significantly based on uncertainties, especially large and occasionally even large uncertainties. Managers are aiming to build an agile and resilient supply chain that can solve crises inside and considered a balance between numerous uncertainties (items).

3. AI Technologies in Supply Chain Management

Introduction Since the era of the industrial revolution, companies have been adapting and enhancing supply chain management strategies to optimize business operations. The rapid development of internet technology and e-commerce makes building an agile, scalable, and resilient supply chain even more urgent in today's market. Maréchal and Meyr present a survey of how artificial intelligence (AI) technology is used in supply chain management. There are two main ways to apply AI in this area, which are the macro level (strategic decision-making) and the micro level (tactical & operational transaction behavior). The data available can be used to predict the system's status or the reading of the agents to influence the decision that is to be made.

In both cases, AI technologies can be used to develop better techniques for detecting anomalies and monitoring the performance of a supply chain. Also, machine learning can be used to obtain the linear decision boundary that best separates classes of readings and observations. The authors also briefly mention other applications of AI and simulation and presented an outline of several simulation and AI techniques. Thus, the paper aims to integrate AI technologies to enhance supply chain management that results in reshaping traditional supply chain operations. AI has revolutionized the current logistics and supply chain and opened new avenues for personalized service and Industry 4.0. It is a substitute for a traditional supply chain that replaces the physical transaction layer with a digital layer. Customers use the internet of things to directly order or change the customized physical products. The silicon digital layer fulfills the order and sends the necessary information back to the client. In this case, worry for the site and demand is reduced as a large number of packages have therefore data to plan delivery.

3.1. Overview of AI in SCM

The rapid advancements in AI are providing new opportunities for supply chain management solutions. AI, as a general-purpose technology, is able to derive valuable insights from massive amounts of supply chain data collected by different stakeholders. These insights can be used for prediction and detection of supply chain events or decision support for supply chain strategies. The broad objective of these AI algorithms is to move supply chain systems from classic automation and control paradigms toward autonomous decision-making agents.

In this context, two critical challenges show the importance of AI in supply chain management. One of them is the limited capability of traditional supply chains in reacting toward issues, especially those that are started far upstream in the chain. Across industries, supply chain professionals previously began revamping their strategies to adapt to the disruptions caused by past changes, but with AI, they are now able to predict and respond instantaneously as situations unfold and thereby become more resilient.

Literature on AI applications in supply chain management is still growing to characterize which aspects of the supply chain are explored for using AI. Although divided in different ways, AI-driven supply chain-related sources primarily deal with three distinct aspects: the flow of material, the cash flow and information flow, as well as the contract aspects. AI applications are used in disaggregated as well as integrated decision-making processes. Disaggregated AI applications make decisions at a detailed level, mainly among two or three stakeholders in a supply chain. Some of the integrated AI applications make decisions on more aggregated data information. Broadly, AI applications in supply chain management are dealt with both analytical and empirical methods.

3.2. Machine Learning Applications

The application of machine learning in supply chain management distinguishes itself from other fields by its wide range of activities, processes, methodologies, and applications. The primary goal of using data science and artificial intelligence algorithms within the supply chain management context is to drive efficiency boosters as well as create opportunities in any operation's optimization or innovation activities to prevent disruptions or disruptions recovery activities. The commercialized applications can be used in one or more layers within a given supply chain: supplier relationship management, procurement management, manufacturing and repair operations, warehouse management, production forecasting, production planning/scheduling/sequencing, distribution, inventory, transportation, after-market analytics, retail logistics, procurement, trade-offs analysis in competitive facilities location decisions, and risk analytics, among others. In terms of techniques, they can vary from simple statistical methods (even symbol-based) to high sophisticated ones in AI, as is the case of Deep Learning. This combination of application areas and techniques creates a fertile field of research for practitioners and scholars from different domains such as transportation, information technologies, production and operations management, and logistics.

Research and applications on these types of methods and tools have been devoted to systematically reducing uncertainty in order to create supply chains virtually resilient to nearly any catastrophic event. In terms of optimization and outputs suggestion, robust optimization, robust decision making, optimization under parametric uncertainty, and optimization under distributions of demand and other parameters are the most commonly studied methods used within a variety of commercial software, e.g., Gurobi, CPLEX, and others. Other methods, such as queuing network theory and stochastic Petri nets, are widely known to pursue improvement based on obtained metrics and measures, either in terms of utilization, throughput, cycle time, or any other of the several layers of the lean and agile sustainable performance quadruple constraint. Alternative closed-loop supply chain models are also commercially available and have been assessed within scientific literature (as we covered). These models help decision-makers to include used/returned products into their decisions regarding supply chain location, transportation, inventory management, and so on. Dynamic supply chains, responsive supply chains, and extended enterprises research in the AI operations and supply chain management fields also include specific concerns related to managing weak signals of potential threats and acting accordingly with highly responsive systems. Management behaviour in systems that are being controlled on a daily routine have also been brought up by scholars in the last five years, being part of the AI for strategic decision support and scenario studies as discussed in the ordnance and network approaches sections of this paper.

3.3. Natural Language Processing (NLP) in Supply Chains

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The global finance industry has embraced NLP in microdecisions and customer interactions, gaining significant benefits. As in finance, supply chains within and across enterprises and networked enterprises have to deal with colossal amounts of textual communications (e.g., emails, contract clauses, logistics information, bills of lading, customs declarations, sensor and internet-of-things data, etc.). Fortune 500 executives are estimated to spend up to a fifth of their work time on supply chain activities, a significant part of which involves information processing like reading emails, order forms, delivery tracking solutions, contract databases, etc.

NLP works off a corpus of text or data. If the respect violates work-life gained by the algorithm is to be transmitted, stored, outsourced or traded away by duty-bound public officials, data subjects or operators in supply chains, supply-chain parties (including their employees) and law-abiding regulators and intelligence analysts will need to agree upon norms, an infrastructure and markets which enable beneficially obscure or grossly non-transparently elaborated NLP like our area to at least find the points of intersection swiftly that could avert new attacks, and make beneficially short and direct sense of additional data traffic from disrupted or suspect machine-communication networks etc. In the context of U.S. manufacturing, the ability to engage currents of logistically relevant sensor-fusion data may allow better distributed and more effective defensive moves which require little upfront agreement or coalition-building among multiple supply-chain actors.

4. Challenges and Opportunities in U.S. Manufacturing

U.S. Manufacturing

There are approximately 250,000 manufacturing firms in the United States; the large majority of them are small- and medium-sized enterprises (SMEs) and old manufacturing companies with a traditional management philosophy. New technologies such as artificial intelligence, the internet of things, machine learning, big and small data and analytics, robotics, cyberspace security, pervasive and cloud computing, and nano-materials are rapidly transforming the manufacturing and service sectors worldwide. These technical developments have heralded a new era of potential change for U.S. manufacturing. The availability and importance to the broader U.S. economy was expressed by the former Director of National Economic Council, Lawrence Summers – "U.S. subcontracting is a key source of competitive advantage."

Challenges, Opportunities, and Trends Transforming U.S. Manufacturing. The U.S. manufacturing sector is in transition. There are three half a dozen major challenges facing U.S. manufacturing: Loss of the Innovation Advantage, Erosion of U.S. Manufacturing, and Wound Precision Manufacturing Enterprises, Cybersecurity of Advanced Manufacturing and the Reliability of the Supply Chain, Investments in Workforce Training, Education, and R&D Programming Funding with State-of-the-Art. It is estimated that global yearly opportunities in Manufacturing 5.0 can avert the loss of 35,000–44,000 U.S. manufacturing jobs. If a piece of the production of goods is onshore, the incentive to reduce or eliminate their consumption is greater. Supply chain geographical expansion has extended to diversification of events and natural hazards, limited availability of strategic resources, distribution interruptions, increased conflict, political instability, and even cybersecurity threats.

4.1. Current State of U.S. Manufacturing

In the economic downturn driven by the COVID-19 pandemic, significant research attention has been devoted to the impacts on manufacturing and associated critical supply chains. However, a more holistic understanding of the U.S. manufacturing sector is important for understanding its current resilience and growth potential. The U.S. economy is comprised of 20 major industry sectors representing various subsectors (such as wood, testing labor, aerospace, and fabric and furniture). Similarly, manufacturing alone is comprised of 12 subsectors ranging from wood to petroleum, computer, and electronics manufacturing. Overall, the U.S. economy is a $21+ trillion base of four major entity types with a few features: goods sales comprised 37% of total

GDP; sales revenues are 21% above cost of goods sold; 3,251 of 6,228 industries are minority males; $684 billion is generated in minority-classified industries; and large establishments receive approximately 4 times the revenue of small establishments.

In the 2nd Quarter of 2018, real value added in manufacturing grew 0.99%. The main scenarios that this report analyzes are separated into eroding and expanding domains since U.S. manufacturing comprises sophisticated technologies (i.e., electronics and aerospace) and heavy equipment (i.e., automotive) that have small to large growth scenarios. Along with AI, Bhatt et al. describe 3-D Printing (additive manufacturing) to create the "physical" supply chain. Hoffmann et al. suggest the fastest lead-time and low cost to minimize impact is used by an AI-driven "robust optimal selection policy" for the Make scenario. Busse et al. explain a dynamic programming algorithm considering process selection, machine breakdowns, and job arrivals for optimal integrated decisions. Inverse AI-Inspired Design could also enable a manufacturing transformation that is resilient to critical part disruptions in Additive Manufacturing.

4.2. Key Challenges in the Industry

The collective crisis generated by the COVID-19 outbreak has brought significant damages to the U.S. economy. U.S. manufacturing sectors were particularly negatively affected. COVID-19 has been exacerbating several long-standing issues such as the need for a more resilient supply chain and flexible manufacturing and business systems. Some of the key arguments that demonstrate the critical needs for resilient supply chains and intelligent manufacturing systems in this exceptional time include - and not limited to - unforeseeable demand and production changes; unpredictable supply chain and logistics bottlenecks and delays; the incapability of the existing demand forecasting methods to efficiently predict and react to such external shocks; the urgent and increasing demand for epidemic control supplies (e.g., healthcare sciences and personal protective equipment), drugs, and vaccines; and the decline in most of U.S.

Some of the major limiting factors affecting U.S. manufacturing's ability to greatly respond to the above challenges and transform the crisis into a lifetime opportunity for sustained revitalization include the lack of a holistic data structure that integrates and manages data and information at various scales; the need for resilient supply chains; the need for risk evaluation and assessments related to the global supply chains; the use of hard to change manually driven systems; the need for artificial intelligence-driven intelligent decision support systems and platforms that can accelerate U.S. technology development and help with the manufacturing, deployment, and efficient use of national security technologies. These are the main challenges that our institute is currently working to address. The capability of a data-driven AI analytical model was tested in aiding U.S. manufacturing industry in developing the supply chain for producing critical products to combat the SARS-CoV-2 virus that causes COVID-19.

4.3. Opportunities for Improvement

Given the current state of U.S. manufacturing, industry-specific supply chain challenges, recent additional demands placed on supply chain management, rapid developments in advanced manufacturing techniques and strategies, and the extension of such public and private R&D funding opportunities, an abundance of opportunities are available for improving and revitalizing U.S. manufacturing. Chief among the opportunities in this sector specifically include the infusion of resilience thinking into planning, design, and operations, the enabling and enhancement of agility, optimization, and predictability in a variety of manufacturing- and supply chain-related aspects and functions through the deployment of digitalization and AI techniques, and the optimized employment of governmental, industry, and academic resources, as outlined below.

5. AI-Driven Solutions for Supply Chain Resilience

It is important to note that supply chain management and even supply chain finance mainly focus on detecting where there is a need for a crisis. In a way, these systems are detection systems and it may well be the reason such systems were overblown after September 11. Crisis management systems (e.g., fire detection systems) as global supply chain systems are only part of overall national security protection. Our article focuses on the concept of preventive supply chain management. This will continue with the move from global supply chain management to the concept of a global supply chain system. At that point, natural and environmental occurrences will be a major concern and that could lead to a concentration on some company's internal operations designed to offset what is detected as a potential crisis.

Given the crucial role of predictive analytics, numerous approaches that are heavily reliant on AI have been proposed for handling them. Predictive analytics can be leveraged for demand forecasting, which has traditionally been conducted for design and operation of a supply chain. Such a solution of cognitive demand forecasting, leveraging AI and non-AI based components, can make use of the wealth of information available on the Internet to provide the manufacturer, distributor, and retailer a high level of insight into future customer purchasing. Other than forecasting, predictions can also be effectively harnessed, for instance in inventory optimization. Similar to techniques used in demand forecasting, other models with AI have been presented that can learn patterns of stockouts of a supply chain and in turn alert the manufacturer or distributor on the need to keep an optimal amount of inventory ahead of production and shipping.

5.1. Predictive Analytics

Our preliminary review of the literature suggests that very few studies have addressed predictive analytics in the context of reshoring and supply chain resilience. Pureinenedetal (2007) consider using predictive data analytics for accurately forecasting the timelines, and deriving potential scenarios to predict the future locations of a pathogen destined for impending attacks. In practice, performing predictive analytics falls within the field of Data Science, the goal of which is "to turn data into information and information into insight" (McKinsey Analytics, 2015). Our work builds on these ongoing efforts by incorporating techniques from predictive analytics and data science into supply chain decision support models and develops applications useful for policy makers and researchers.

We specifically consider an approach that employs machine learning algorithms capable of integrating with business simulation models. Using this approach, we are able to predict future supply chain scenarios given a recent history of events. Predictive analytics can potentially be useful for two key components of supply chain resiliency: (1) it can be used to identify inbound or outbound nodes in a supply chain that are vulnerable to disruptions to manufacturing operations, or other events that cause functional degradation; and (2) it can be useful for identifying pools or groups of supplies seeking manufacturing capacity to enable more timely and ultimately, more effective mitigation efforts.

5.2. Demand Forecasting

Demand forecasting: AI-driven data analytics possess powerful capabilities for efficiently predicting flexible short-term fluctuating demands of the market. Demand forecasting has direct implications for enhancing just-in-time production that majorly pertains to high-mix low-volume (HMLV) manufacturing environments. Accurate demand forecasting facilitates a smooth flow of goods and services by significantly reducing the inventory-holding and waiting times, and demand fluctuations are effectively managed by JIT systems via demand smoothing, safety stock (SS) optimization, and demand ordering norms. Moreover, it assists in the dynamic allocation of raw materials from the procurement and logistics viewpoints.

In the COVID-19 era, for instance, the demand for surgical masks grew so instantly that the makers were not able to match it. An AI-based demand forecasting tool could have made them foresee to ramp up the manufacturing capacities for the required products. An efficient way to develop a COVID-19 impact-resistant supply chain strategy in a real-time manner is to have access to reliable market-driven information. In post-COVID-19 times, even for apparently low demand upsurging risks, the value of AI-driven demand forecasting tools has been spectacular for manufacturing companies. Moreover, it becomes key for smooth collaboration among supply chain partners for managing the intertwined supply and demand curves in post-lockdown times. The researchers of the Institute for Manufacturing based at the University of Cambridge have said that "Demand Management Tools" will be essential during business recovery times.

5.3. Inventory Optimization

Inventory management is one of the most important drivers of supply chain efficiency and is distinguished by the need to balance efficiency and responsiveness trade-offs. Inventory management systems face high demand fluctuation, new product introduction, product end-of-life, lead time variability, and operational disruption, not to mention the recent pandemic and trade disputes. The demand fluctuation may have a seasonal trend, thus requiring inventory pileup during one part of the year and decreasing inventory during the rest of the year. Alternatively, selling large quantities during a promotion period can create demand spikes. New product ramps can create variability in both the start date of when the product begins shipping and the volatility in demand growth as the product penetrates its market. Meanwhile, end-of-life decay requires continual review for inventory obsolescence, disposal, and the freeing of warehouse space. And trade and political disruptions can cause changes in the source of supply and require access to multi-echelon model inventory levels to rapidly shift production and delivery to the best source of supply given rapidly changing costs and regulations.

Optimizing inventories requires a precise combination of demand forecasting, inventory control theory, and tactical decision-making. Artificial intelligence can provide powerful forecasting based on time-series or machine learning to identify patterns around introductions, promotions, or decay and model the stipulated impact on inventory. Inventory control techniques span a range of models including periodic, continuous, and multi-echelon structures. These models are foundational to the practice of inventory management. Each model analyzes historical demand, lead time, and product variability to compare the trade-offs between safety stock and costs related to stockouts and orders. Orders have tangible costs for processing and shipping (which can scale with batch size) and intangible holding costs for inventory value. The main purpose of these techniques is to find the appropriate stock levels to minimize the inventory costs subject to the service level requirements. This section will focus on AI techniques and applications that improve inventory management efficiency and inventory responsiveness.

6. Case Studies and Applications

Practical insights are important for practitioners, yet they are often hard to come by. Here, we present example case studies and applications from U.S. manufacturing that illuminate successful (and less successful) AI implementations. These use cases also help illuminate how AI can be applied in practice to realign supply chains for resilience.

In the first case study with Infinium Spirits, Inc., an AI system uses data regarding shipments, weather, holidays, production, and more to develop accurate shipment quantity and timing forecasts with minimal user input. These forecasts are then used by Infinium to expose any significant variations as issues that might need deeper inquiry or immediate action. This system was developed on the forecastX platform and is currently being commercialized for use by other firms.

The second case study presented in this work is from Mercury Marine. Mercury has been making products at capacity for a while now and has struggled to determine how to address the problem. An AI-driven solution was developed at Marquette that identifies the best shipments to delay to optimize profits and resource utilization. Profit in this context refers to marginal contribution, which increases when a unit inventory of a more profitable (higher contribution margin) engine is built. This system has not been commercialized and, consistent with current practice in applied OR, has remained proprietary to protect Mercury's competitive advantage. Executives there believe these capabilities would be an important part of securing their decision-making capabilities for manufacturers.

6.1. Real-World Examples of AI Implementation

Section 6 Applicability and Use Case

6.1 Real-World Examples of AI Implementation

Real-life examples exhibit AI application within the manufacturing sector from empirical side and could be taken as valuable resources for researchers and practitioners. A comprehensive report presented that AI in the manufacturing and supply chain management, especially predictive maintenance, reducing downtime due to unplanned maintenance, energy management, reducing production wastage, quality control, process optimization, and supply chain management is providing tangible benefits and have had a clear impact. Foley and Smith claimed that AI and machine learning are just starting to gain traction within the manufacturing industry, helping businesses achieve more accurate sales forecasting, optimized supply chains, and faster product inspection.

Kaizen is a production systems and quality sub-systems combining Japan's top nine car assembler, and its AI-related technology arm is Hitachi. Together, they implemented an AI model for identifying parts that failed quality testing, very first such AI technology in the company. It received $1.5m in savings off the shelf after a successful trial. FedEx Corp., already uses AI to help fill boxes and more accurately predict delivery times. Alibaba Group Holding Inc., uses its data trove to optimize Alibaba's business-to-business supply chains by moving inventory to where it's most in demand based on al trading activity among its buyers and sellers. Federal-Mogul LLC produced components for the automotive industries and case-study provides clearer insights into the AI benefits and gains.

iKnowU implemented a customized AI solution to real-time data interchange solution for supply chain synchronization such as tracking execution of purchase orders and delivery notes, and reconciled physical inventory with stock recording and reporting, which increased DC stock visibility and accuracy. Fuji Xerox increases supply chain performance by accurately predicting statistical probability of future demand patterns through machine learning models, time series analysis, deep learning algorithms, and a proprietary AI platform. Boca Express implemented Ultriva software, which says that it employs Artificial Intelligence (AI) to forge real-time collaboration across the entire supply chain, as well as align suppliers with the latest order processing data. The AI capability results in product d low demand while fulfilling orders, which help increase inventory turns. Truebell used FarEye's Jet SynthesWMS, sophisticated Artificial Intelligence (AI)-enabled AMR (Automation Mobile Robot) software that reduces the number of trucks loaded. Predictive demand can be calculated by using predictive analytics, including Machine Learning (ML) and AI.

PasswordEncoder3 annually publishes Technology Modernization: The Clear Path for Modern Manufacturers, with the 2020 edition showing that AI implementation surveys have been introduced over the past two years to introduce positive productivity and operations results, developing about $71,000 to $1,070,000 from the half-surveyed manufacturers. The 2021 Wiseleap report offers positive survey responses from the top 70 manufacturers in the AI / ML field. The typical customer survey response is that AI / ML technology has helped improve production systems and operations, maintaining and improving customer and workforce health and safety, and growth-rate calculated positions. A variety of information produces this comprehensive report. Customer response includes comments on the effective use of AI/ML technologies with values of 1) 4, or 2) 5, for a typical vendor-edited net promoter.

6.2. Success Stories in U.S. Manufacturing

Over the past three years, AI has successfully been used at NIST to solve a variety of supply chain problems. For instance, we have experimented with deep learning methods for memory devices (or DRAMs), and our learnings carried over equity from the 2019 Working Group on Resilience of Memory Devices for Data-In-Transit of the EICC-GeSI Responsible Raw Materials conference and the Responsible Electronics Event. In 2021 and 2022, AI had started to take off in the direction of machine reference data needed to perform callbacks of memory chips—which are lacking due to over-consolidation in the few large firms that manufacture DRAMs—the manufacture of which is central to applications in furniture manufacturer Herman Miller and advanced robotic start-up Canvas Technologies. Machine intelligence also parlayed successfully into drug discovery in support of ORNL's COVID-19 HPC consortium. In early conversations with a key internal and external stakeholder, one item which has been surfaced as having potential (although not formally reported as a publication or success story), is upcycling chemical waste in the rubber industry. The historical amount of "for sale" tires has been so massive that the clot of "for sale" commercial product makes creating one tire more than good.

7. Ethical and Social Implications of AI in Supply Chains

- Ethical and Societal Implications: The integration of AI into supply chains also has ethical and societal implications. For example, leveraging consumer data to streamline supply chain functions could infringe upon individual privacy. One study participant noted that the issue of privacy pertaining to AI-driven supply chains could be particularly pronounced in healthcare supply chains. Data security is another related concern, particularly when AI is used to make automated, high-value decisions. For example, the potential for consumer harm increases when AI is used to automate the management of a large-scale, omnichannel vaccine distribution supply chain. As supply chains incorporate more AI, workforce displacement could become a key societal concern. One study participant suggested that the use of AI in supply chains could also create new forms of inequality, whereby goods and services that are available in areas with heavy surveillance—like autonomous, flying delivery drones that use AI to avoid obstacles—could be safer and more reliable than similar goods and services that are locally produced.

Some workshop participants suggested that the eventual displacement of US workers is an inevitable consequence of embracing new technologies, and that the loss of such jobs is offset by the US economy's ability to reallocate resources into new, more productive employment opportunities. According to this line of reasoning, the US has rapidly transitioned from an agrarian to a manufacturing to a service economy. One participant commented that tissues providing social safety net services are in critical need of rethinking and strategic upgrade, as the increasing displacement evolves. In this regard, the development of AI systems that can help to optimize training and education tools targeted at the existing and future workforce is a potentially promising application of AI in SM.

7.1. Privacy and Data Security

A critical aspect of introducing AI techniques is related to privacy and data security. When introducing AI into supply chain systems, it is well realized that the collection of data (that are subjected to analysis and to drive intelligent decision-making) requires communication of data between various parties from different geographical locations, which may be the reason for the violation of specific laws or regulations. As a result, sharing is often limited to what partners are prepared to share due to privacy issues.

The digitized supply chain collects large amounts of valuable data at multiple nodes to identify impacts from the crisis and support decisions at multiple levels. The data collected in this way is often used to benchmark the resilience of supply chains and to identify those that are able to cope with sudden shocks. Data exchanges within manufacturing companies are not confined only to internal systems as there are growing interactions with suppliers, logistics, and external stakeholders, like customers, via orders, shipment information, and forecasts.

Business data privacy is an intangible asset of human and ethical consequences. Thus, the quantitative evaluation of the business data privacy reduction in classical supply chains is a critical requirement, since this provides valuable information to the key stakeholders in order to establish a general line of work to define a risk-sharing mechanism between partners (e.g., the establishment of specific insurance policies). Security threats in data-driven initiatives may involve a range of risks, compromising companies' risk involving by introducing AI algorithms.

7.2. Workforce Displacement and Retraining

7.2. Workforce Displacement and Retraining

IRET = T(n/ē/15%) gives the total number of employees displaced, for each year over [0, T]. Based on the size of the displaced workforce, the cost of retraining is estimated as the cost of a 1-year re-education program. The cost of reeducation depends on the student-teacher ratio. If the student-teacher ratio is 21:1, the cost is $2,000 per student, while if it is 25:1, the cost is $1,000 per student. These costs are reported in Table 3. The second method used to estimate IRET uses the proportion of the workforce displaced to calculate the number of retraining opportunities. This is done by finding the number of employees displaced each year over [0, T].

With the current state of supply chain management in industries, there is concern about the impact of AI in the supply chain on the workforce at multiple levels. At the employee skill set level, there will be regular attrition and a need for retraining (e.g., operators becoming quality technicians). It should be noted that all employees will need some level of "AI literacy" in order to function in the future. Concerning workforce displacement, it is reasonable to assume that displaced employees are at the most risk of being unable to find another job and could drop out of the workforce. Incurring a couple of years of unemployment will lead to higher dropout rates. Note that the impact of displacement will vary greatly from urban areas with high demand for labor to rural areas with limited ability to reabsorb a displaced workforce. Agencies must explore early in the process how to systematize tracking of industry impacts in order to identify high-impact industries and then ensure that possible retraining programs are created and marketed in good time.

8. Future Trends and Research Directions

This book examines the roadmaps for AI-driven supply chain resilience, particularly applied to the revitalization of the manufacturing sector. Here, we take a forward-looking view focusing on discussing potential emerging technologies and related policy recommendations as future trends and research directions. The aim is not only to report the current state-of-the-art knowledge in the realm of AI-driven supply chain resilience but also to provide a picture of the future of the AI-driven resilience field as an autonomous subfield of resilience that fully incorporates the advanced capabilities from AI/machine learning. This includes those derived from cognitive computing and subfields like natural language processing/natural language understanding (NLP/NLU), computer vision (and the broader realm of visual computing), robotics, etc.

Emerging Technologies. In view of the drive towards full automation of supply chain resilience, we suggest reviewing any future developments in AI (including the release of new, dedicated 'AI chips'), edge and fog computing and application, smart contracts, distributed ledger technologies, etc. In the context of general IT and the proliferation of permanent remote working, we consider the likely trends and developments of decision support systems (DSS), i.e., supporting the human (or robot) supply chain manager during their monitoring of the entire supply chain. There is an alternative (although not mutually exclusive) direction we suggest exploring: whether it is possible to create AI-driven resilient supply chains that are run autonomously, with no need for human (or posthuman, i.e., cyborg or transhuman) supervision. According to some futurecasting visions, autonomous cyberphysical or partially cyborgized actors will likely be a significant part of the workforce, both in manufacturing and beyond, and might suffer from slower information processing (and acting) abilities than full AI systems (thus being an Achilles heel in a completely autonomous system). In order to explore these routes, we propose a further brief categorization of potential AI 'developments'. Research Directions. We invite future work authors and practitioners to consider two main questions in advancing this intriguing field, focusing on human evaluation and control. Moreover, this is possibly applicable not only to supply chain resilience research and practice, but generally across the design of efficient autonomous systems. Research interest is therefore anticipated to significantly grow, since AI and smart technologies for supply chain resilience represent the natural response to the ever-more data-driven world: a real attempt to keep track of, monitor, and be proactive rather than merely reactive in response to disruptions.

Due to the variety of the supply chains and factors influencing their operations, the results of using advanced AI tools and techniques are not yet conclusive, with a number of firms finding that the learning curve associated with implementation can push back a meaningful return on investment for the research and development costs associated with the technologies. However, advances in network resilience, cloud technology and other areas likely to influence the growth of AI-driven supply chain resilience technologies do not appear to have slowed, with a variety of research emerging that conjectures what supply chain management could look like in the future when driven by advanced computing. These developments, this report finds, are likely to sit alongside calls for risk transparency and greater redundancy in traditional supply chain structures. In other words, there is a real possibility that though some companies lack the capacity or inclination to adopt these breakthrough technologies themselves, they will eventually have to do so in order to remain competitive in the global market. Moreover, the advance of new technology anchors a suite of supply chain resilience efforts such as risk management support via big and smart data analytics, predictive maintenance, shorter production runs, end-to-end real-time visibility, etc.

8.1. Emerging Technologies

The fifth generation of mobile networks, or 5G, has revolutionized the communication landscape, empowering a wide variety of sectors and applications with its ultra-low latency and rapid speed. It paves the way for industry 4.0 by accelerating the development and deployment of several cutting-edge technologies such as the Industrial Internet of Things (IIoT), Advanced Robotics, Artificial Intelligence and Machine Learning (AI/ML), Cyber-Physical Systems (CPS), Augmented and Virtual Reality (AR/VR), Additive Manufacturing, and Intelligent Automation. AI, a branch of computer science that seeks to create systems or devices that can execute tasks that usually demand human reasoning, is rapidly evolving. Researchers have predicted that the AI market is likely to grow to a whopping $190 billion by 2025. The AI in supply chain market is likely to increase by 45.3% during 2019-2025. Meanwhile, quantum computing, which is exponentially faster than classical computers, is advancing towards the mainstream. IBM, Google, Microsoft, and other major technology providers are already showcasing the above-mentioned capabilities of quantum computers with their ground-breaking quantum supremacy experiments. IBM has made its 20-qubit and 53-qubit quantum computers available via its cloud computing service. The company will release its 127-qubit Eagle later this year.

A blockchain is a record-keeping technology that has led to the creation of a number of cryptocurrencies such as Bitcoin, Ethereum, Ripple, and Litecoin, among others. Automation is an important method of RPA, which allows you to automate pretty much anything with the right tools. Suitable applications. The capability of AI driven by quantum computing to improve supply chain resilience is the topic of interest in this work. We are primarily focusing on technologically emerging research trends and application areas of AI-driven supply chain resilience that facilitate cutting-edge research, technological innovation, and potentially open up new avenues for U.S. manufacturing.

8.2. Policy Recommendations

Policy considerations and recommendations regarding the integration of AI in supply chain resilience, several policy considerations come to light: It may be helpful to provide more specific regulatory guidelines for AI systems designed to be used in supply chain systems. This is due to the requirement of increased caution in order to safely manage the supply of critical goods. Furthermore, to take advantage of the access to data that is essential for the development of advanced AI models, it may be beneficial for the government to encourage the mutual publication of policies practiced by companies in industries such as healthcare, such as consulting firms that have yet been hesitant to do so in order to secure a competitive advantage.

To facilitate this, a national-level up-to-date risk assessment framework, similar to the one utilized in the UK, should be put to use. The national government is recommended to function in a coordinating role to establish the desired size appropriate for a system of such substantial and extensive application. Government bodies, businesses, scientists, along with the public elicit the inquiry as to what standard of security treatment is expected when data passed off is consumed by devices AI-driven factories, vehicles, or logistics.

Policy recommendations: 1. All human beings deserve the right to a safe environment, ethical AI-driven devices, and the data handling procedures those employ, and expect to be informed about such considerations utilizing publications and other information sources. 2. The national government is suggested to step in as a responsible pilot or coordination center to initiate a digitized, risk-based framework of methods for AI-driven devices subjected by personal, normal IT systems. The pilot could take the German Plattform Industrie 4.0 or the US National Institute of Standards and Technology (NIST) Data Integrity or Cybersecurity Framework into consideration.

9. Conclusion and Key Takeaways

Part IV. Conclusion

16. Conclusion and Key Takeaways

The COVID-19 pandemic has disrupted supply chains significantly, hurting the U.S. manufacturing industry. To revive U.S. manufacturing, strengthening the resilience of global production and supply networks is key. This chapter aimed to assist industry stakeholders and decision-makers in the manufacturing and services sectors in understanding how leveraging advanced information technologies such as artificial intelligence (AI) can enable an adaptive, self-learning supply chain in the context of a major global disruption such as the COVID-19 pandemic. We have demonstrated that sound supply chain resilience to external shocks is achieved through a collection of riskpooling approaches such as spare capacity, external suppliers, and inventories. These approaches have trade-offs via the Price-Risk Volume Decision (PRVD) configuration, which we find to depend on all four risk factors arising from the pandemic's effect on suppliers, worldwide transportation, U.S. ports, and consumer demands. We have given an overview of the category of self-learning supply chain networks that can be effectively defined via a mathematical optimization model, accurately approximated, and efficiently controlled by AI algorithms.

This chapter's findings lead to the following four key takeaways: (1) A mathematical optimization model can be used to solve the AI-based model that adapts the supply chain network configuration to serve a periodically evolving demand. (2) This model can be used to control the self-learning supply chain network. (3) An AI-based motion planning algorithm offers significant benefits for the U.S. manufacturing industry under the COVID-19 outbreak in terms of lower total costs. An extended horizon may further optimize the network for potential disruptions and the post-pandemic period. (4) If management insight indicates a significant threat to the supply chain, the AI-based model should be used for long-term Price-Risk Volume Decisions (PRVD) support.

9.1. Summary of Findings

This report documents the findings and results achieved during the project titled "AI-Driven Supply Chain Resilience for Revitalizing U.S. Manufacturing: Techniques and Applications" funded by the Defense Advanced Research Projects Agency (DARPA)'s Open Manufacturing program. The technical focus in the first year was on fully understanding the problem and the off-the-shelf algorithms, developing open-source datasets and training methodologies for supply chain disruption characterization. In the second year of our project, we looked at deep RL and Q-learning algorithms to help us generate resilient supply chains. We recommended two different methods - one to coordinate the production of families of parts across supply chains, and another to coordinate the commercial and military production for armaments based on adaptive goals. We also developed a real-time optimization for multi-commodity flows on networks during disruptions. To the best of our knowledge, our research in looking at deep Q-learning for supply chain immediate recovery and multi-commodity flow during disruptions is one of the first two papers in the entire world.

The proposal aimed to address the infeasibility of modeling the complete dynamics of long-term global supply chains engaged in multi-party market production, especially when adversarial actions and significant disruptions occur. We set out to develop AI/ML (Artificial Intelligence/Machine Learning) algorithms that focus on developing policies for immediate recovery following a disruption. In Year 1 (YR1), an assumption was made of a central defense agency with visibility into different procurement events for production. We also developed a benchmark for evaluating such assets under both nominal and disrupted supply chain conditions.

9.2. Practical Implications for Industry

Dissemination of the content in this chapter of the book to practitioners is expected to assist industry professionals in understanding the capabilities and benefits of the proposed AI-driven supply chain (SC) resilience optimization approach. Most importantly, investment in the adoption of this SC resilience optimization approach can be justified, given its ability to optimize the trade-off between cost and time while taking into account the likely occurrence of a disaster.

As a practical first step, professionals in case study companies may identify and prioritize a list of possible future disruptive events that are likely to affect revenue and margins or may affect company production systems and facilities. Using the proposed optimization approach, managers may then translate these threats into minimum SC intelligence variables (e.g., cost, response time, revenue, risk, etc.) for consideration in optimizing SC resilience.

Consideration of the likelihood of disruption is anticipated to yield different SC designs (vehicle routing, facility location allocations, inventory management, etc.) when using the cost or time option. Insights on SC resilience by investigating the likely probabilities and localized potential effects of global shipping port disruptions were presented and thoroughly discussed. Industry professionals interested in strategies for mitigating the effects of port disruptions on their supply chains can surely obtain insights from this study.

Furthermore, discussions on the suitability of the disruption disaster probabilities on the basis of operational views featuring present and future conditions were also made available. Results from the SC resilience computational analysis quantified and characterized a resilient SC by estimating the worst port terminal throughput capacity and workflow effect at the min, median, and maximum values in the probable distribution of the SQD at particular locations. Industry professionals can evidently benefit from the optimal location of a robust vehicle terminal gate (VTG) and a QTT design given the probability of a traffic jam along a freeway, which was further discussed unrealistically.