

Component Scarcity Forecasting and Multi-Tier Supplier Risk Modelling: AI-Driven Supply Chain Resilience for U.S. Technology Product Manufacturing

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1. Introduction, AI-driven Supply Chain Resilience in U.S. Tech Product Manufacturing

The purpose of this paper is to discuss AI tools for supply chain risk management. The major part of this paper is in the fifth section, dealing with the techniques, which also includes sections on using AI-based simulation techniques to evaluate potential impacts of alternative supply chain design strategies and guiding the agent in supply cabotage decisions.

The application of the AI-based techniques for US Tech product manufacturing discussed in the paper is given below. Artificial intelligence and machine learning provide new ways to understand and adapt a supply chain system in response to a disturbance. In this research, we demonstrate how intelligent agents and AI-driven simulation may automate a supply chain reconfiguration process to strategically enhance supply chain resilience. Such a technology can revitalize U.S. tech product manufacturing by reducing barriers of supply chain resilience investments. We demonstrate this capability in systems for reshoring and decarbonizing the production of microcontroller computers for smart infrastructure and industry applications. As part of the demonstration, this research includes recommendations for attracting private sector investment in U.S. tech product manufacturing through a campaign to prove the economic value of supply chain resilience investments.

This paper is structured as follows. The next section is the background of supply chain problems and reshoring in United States manufacturing. The second provides an overview of use of AI for simulation-based risk management in supply chains. The third reports on the decision support systems in U.S. domestic reshoring initiatives fitting our problem of interest and our stakeholder context. The fourth is the supply chain domain and problem statement. The fifth reports the description of our AI-driven

methodologies. The sixth describes prospective technology commercialization, our strategy for capturing the needs and requirements of the manufacturing stakeholders, and application recommendations for policymakers interested in public-private partnerships for national infrastructure and logistics resilience.

1.1. Background and Significance

In World War II's initial days, U.S. companies dramatically altered their fields of expertise to manufacture supplies for war. Today, as the COVID-19 pandemic has disrupted "business as usual," the supply chain and component shortages contribute to federal policy discussions for revitalizing U.S. domestic tech product manufacturing. With the existing manufacturing ecosystem significantly differing from that which existed 20 years ago, companies search for secure and more resilient solutions to risk. Raw material and finished goods inventories may satisfy sudden disruption-associated material flow, but long-term storage and obsolescence defy economic justification. According to commentators, favorable trends point to U.S. manufacture as being more achievable than 10 to 20 years ago, but commercial companies' viewpoint on such a move generally remains cautious. In summary, an important technology-gap barrier is that the majority of current resilience is managed reactively rather than proactively.

Our goal in this new NSF-contracted resilience study is to identify supply chain resilience, particularly for components, and how artificial intelligence (AI) can be utilized. Our purpose is to aid the search for the next technical improvements by taking a comprehensive look at current resilience technologies and identifying overlooked possibilities. The use case for this work is photonic components while explicitly seeking generalizations to more electronics, for which photonic opportunities are similarly vast. Because photonic components are increasingly tightly bound to the processing and storage servers and cloud of major U.S. and international companies, these companies have a risk in long-chain acquisitions of components to link these networks. Additionally, customers in supply chains are increasingly looking for insurgency-inclusive supply chain change to provide added resilience and security.

1.2. Research Aim and Objectives

This essay presents an attempt to explore the concept of supply chain resilience and its significance. It, in particular, aims to offer numerous techniques using artificial intelligence and their ability to improve resilience. In keeping with the special issue's

strategic contributions, we also present the most recent advances and applications of these AI-based supply chain resilience techniques using a comprehensive review of the literature.

Given the nature of the overarching focus of this special issue, this essay's investigation of supply chain resilience-related topics is based on a large-scale quantitative literature review. First, we consider the definition of supply chain resilience and its relationship to supply chain management and tactics. Second, we identify recent advances, techniques, and applications of AI-driven supply chain resilience using a set of articles focused on AI-based supply chain. Third, we present the AI-driven resilience solutions for manufacturing, including the techniques and technologies directly related to resilient manufacturing. Fourth, through a qualitative literature review of the methodologies and practices related to the reorganization of the U.S. tech product manufacturing, we investigate the practical potential, limitations, and concerns of AI-driven supply chain resilience. Finally, we point out the theoretical and managerial implications as well as the directions for future research.

2. AI Technologies in Supply Chain Management

Supply chain management is a technology and data-driven field with a multitude of interlinked systems and resources that relies heavily on data to coordinate and optimize activities. Inventory management, procurement decision making, and efficient transportation planning are critical for enhancing total supply chain competitiveness. As volumes of data continue to grow increasingly rapidly, AI is being increasingly used to assist decision makers in strategies for managing and deploying prodigious amounts of data that can predict and help with strategic supply chain decision making in addition to routine operations involving a myriad of partners and suppliers. For example, AI-powered supply chains help optimize operations such as network configuration (where to locate various units such as factories, warehouses, etc.), response strategies for managing precarity and disruption risks in supply chains (such as multiple sourcing and time buffers), resource allocation, establishing investment priorities, predictive maintenance, final product customization, and renewable energy deployment.

Physical and financial interdependencies and the magnitude of data exchanged in international automated supply chain networks (China is a major supplier of electronics) constantly risk cybersecurity breaches potentially leading to erosion of trust and

financial losses in both U.S. firms as well as the technology product overall supply chain. An investment in AI technologies for electronics supply chain resilience is therefore beneficial to U.S. technology product firms, electronics supply chain partners, governments, and customers (at large) to recover and boost U.S. electronics production. In the subsequent subsections we will provide an in-depth overview of various AI-based techniques to supply chain management currently employed.

2.1. Overview of AI in Supply Chain Management

AI technologies, particularly machine learning (ML) and natural language processing (NLP), are being increasingly adopted to address the myriad challenges faced by supply chain stakeholders and managers. In essence, AI embraces a set of tools and methods that enable the simulation of "human intelligence" and the ability to learn from turnover data. Overall, AI has been used to design, optimize, and manage the supply chain at different levels in an automated manner, taking both "hard" and "soft" data, or company reports and financial figures as well as crowd-sourced and media information, as input. A helpful data-driven supply chain management framework is provided in Fig. 4, recognizing processes at different functional levels, from demand forecasting, moving onto production/operations strategy, and then on to managing the inbound and outbound logistics flows in an adaptive supply network.

The modern supply chain management/operations research literature describes two main approaches for solving a supply chain while accounting for digitization and the utilization of AI. The first approach exhaustively evaluates the entire decision space and finds an optimal solution using exact optimization, e.g., stochastic programming, dynamic programming, queueing systems, etc., considering the specific method used in a given application. Only recently, significant advancements in AI have been made, most notably with respect to reinforcement learning. More details on these methods are found in the following sections, in which we provide an overview of AI developments directed to supply chain management strategies (subsec. 2.2) as well as at the operation/tactical levels (subsec. 2.3) of decision making.

2.2. Applications of AI in Supply Chain Resilience

Robust and adaptable supply chains are essential for ensuring the resilience of various sectors. AI offers new techniques for modeling supply chain decision-making and for the real-time reshaping of material flows in the face of disruptions. To this end, AI can

provide supply networks with early warning systems for a wide variety of risk factors. AI prediction techniques can be used to develop proactive actions for disruptions in the supply chain flows of raw and intermediate materials for manufacturing, or for the warehousing and distribution of finished products. Additionally, AI simulation and modeling techniques can be used to develop contingency and resumption plans in supply chain networks when a given disruption event is experienced, or anticipated in the short term, e.g., due to seasonal weather-related production volatility.

Successfully implementing AI tools in supply chain resilience requires models for the prediction of supply, demand, and potential disruptions. Objectives include the dynamic selection and parameterization of logistics options and coordination with downstream and upstream partners. A current state-of-the-art supply chain solution is a decision support system that uses data mining to detect and respond to disruptions. To move from this current state of disruption management to a bio-inspired and AI-driven computing-based implementable resilient solution, the development of several other algorithmic approaches—e.g., employing prediction models in addition to reactive solutions currently implemented in practice—must be considered.

3. Challenges in Supply Chain Resilience

Supply chain resilience represents an increasing concern for both researchers and practitioners. Comprehensive studies reveal that firms and networks experience rising vulnerability and complexity driven by hyper-competition. Several factors, such as the partial use of standards and regulations, the rising modern portfolio theory, the lean principle, and practices related to transparency and risk management, are constraining the improved resilience. In order to anticipate and respond to such dynamics, an undoubtedly important challenge in the field of resilience focuses on assisting firms and networks to restore the desired flexibility within production and logistics functions.

In addition, further recognized ground features accompanying resilience to operational risks include, for instance, irreducible environmental constraints, the characteristic super-exponential growth of a system in crisis, multi-period traits in sustaining the globalized economy, and an overall scarcity. However, little empirical research deals with empirical, macro-based investigations relating to analysis, mapping, and interpretation of possible solutions to enforce supply chain resilience. Thus, the contribution of this paper stems from an empirical investigation in the context of the

U.S. supply chain and, particularly, U.S. tech product manufacturing. It allows providing an understanding of the hard-won lessons and good practices with a focus on how to revitalize the resilience for the U.S. supply chain.

Supply chain resilience entails tradeoffs between maintaining high service levels and lower inventory and operating costs. An upper echelon survey conducted with the top 150 public U.S. firms reveals that global and regional supply chain vulnerabilities rank as a top threat to business operations as they customer or market share (ranked as a moderate/very significant risk by 53% of surveyed firms). Additionally, such risks are coupled with a rising number of rebound threats, including, for instance, financial difficulties and business disruptions.

U.S. supply chain vulnerability direction tends to shift from an Asia-United States route to a Mexico-United States logistics route due to multiple reasons. From a geographical, political-economy, and cultural standpoint, Mexico stands as the U.S.' first-ranked trading or goods supply partner, with trade along reached over 1.64 trillion U.S. dollars prior to 2020, with over 78 billion U.S. dollars of goods crossing the U.S.-Mexican border, on average, in a single month. From an operational and economic standpoint, Mexico is the U.S.' first supplier of goods trade exports, with surges in the car industry, electronics, and food and beverage sectors experiencing an unprecedented rate of growth. Despite this, the U.S.-Mexican partnership fosters vulnerabilities, including, for instance, rising port-of-entry border congestion levels causing potential product/service delivery delays. A dynamic link between supply chain resilience and maintenance and resilience transportation system capacity is revealed. Firms, in general, are impacted by some type of supply chain disruptions, with disruptions correlated with firm policy change activity, despite only a subset of firms being impacted by the specific type of supply chain disruption.

3.1. Traditional Challenges

Supply chains (SCs) face many challenges in preserving their resilience. These challenges render SCs fragile and susceptible to various risks - a recent example being the COVID-19 pandemic, forcing the U.S. and other nations to address foreign dependency in the manufacturing of various tech products. Some existing AI-driven products may have the potential for SC resilience analysis and even prediction. In the

following, we briefly outline the root causes of these challenges, as well as SC-centric techniques that have been used to tackle them.

Traditionally, SCs may suffer from two types of vulnerabilities: micro-level and macro-level. Micro-level vulnerabilities include low production capacity, operational inefficiency, and poor quality management, which may eventually lead to disruptions, bullwhip effects, and amplified risks and losses at the macro level. At the macro level, certain economic/business practice decisions may also contribute to weakening supply chain resilience. For example, SC players may rely on a single source/asset for cost effectiveness, or industry practitioners may be reluctant to enhance SC resilience if the costs of doing so exceed the potential benefits. Additionally, SCs are increasingly vulnerable to new challenges such as natural disasters, terrorism, financial crises, and pandemics. These challenges may exacerbate existing micro and macro-level vulnerabilities, as demonstrated in the COVID-19 pandemic, leading to components and/or resource shortages, demand volatility, stock price declines, allocation rationing, layoffs, and production stoppage.

3.2. Emerging Challenges in Tech Product Manufacturing

Tech product manufacturing has a multi-level supply chain, from raw materials to final end-products, and comprises numerous manufacturing and assembly stages. Supply chain resilience (SCRES) maximizes the supply capacity of intermediate products to prevent complete supply chain breakdown and maintain the production of finished products. Out of 250 U.S. manufacturing verticals, we focus on four of the top ten industries based on annual producer shipments. Tech product manufacturing is becoming more susceptible to disruptions because of its cross-vertical nature. Companies in this tech product manufacturing ecosystem, especially SMEs, face this consequence without proper focus or attention on the concept of their SCRES.

Manufacturing systems have been the main target to address SCRES, due to the complex global network of suppliers that are required to support them. During the COVID-19 pandemic, the entire tech product manufacturing ecosystem was disrupted, and many products became unavailable or were severely delayed due to poor SCRES. The prevalence and urgency were quantitatively estimated in. Tech product manufacturing is determined by various factors that are necessary to be explored and considered in order to properly address SCRES in this domain. The most prominent factors include

supply chain complexity, geopolitical risks, demand forecast deviation, inventory management issues, lack of communication and visibility, and the demand for personalization. In this research, we categorized the characteristics into three main latitudes, namely commercial, operational, and socio-political, to identify the gaps and prioritize them.

4. AI Solutions for Supply Chain Resilience

AI technologies such as blockchains, algorithms, and simulators can mitigate many of the previously mentioned challenges. In the realm of digital transformation, blockchains are currently one of the top-of-mind technologies for supply chain use cases. They promote transparency and information sharing, make it easier to comply with regulations and standards, and eliminate intermediaries. Since a blockchain is an indestructible digital ledger, it reduces the problems related to lack of trust, information asymmetry, and confidentiality. A blockchain creates a permanent digitized chain of transactions which are distributed and immutable. This prevents fraud and hijacking, reduces counterfeits and the black market, and decreases broken or lost spoilage by more effective parts and optimal routing and scheduling.

AI systems can utilize increasingly sophisticated algorithms and simulation-based parametric and nonparametric models with agent-based, neural, fuzzy logic, linear/nonlinear programming, and integer optimization systems. These systems can provide supply chain planners and decision-makers with data-driven, multilayer visual analytics on probable variations towards goals and operational drift, root causes of supply chain risks, and applicable prevention and recovery/resiliency strategies. Another application in AI-driven supply chains is decentralized decision-making processes using edge computing platforms. These platforms can process, analyze, and exploit data at its origin, making complex decisions in packet-optimal time. In a hardware-constrained environment, edge computing systems can shrink the attack surface of the Internet of Things.

4.1. Predictive Analytics

Predictive analytics methods are increasingly being used in AI solutions to predict denser change points, helping in the development of better buffer management and configuration design. Entrepreneurs also utilize predictive analyses to predict stock movements and demand fluctuations. By using predictive analytics, companies can

access data from all locations to improve forecasts, prioritize high-gain predictions, predict capacity resulting from supplier failure, intellectual property theft, price, and other changes, and send fast recovery signals to resilience supply targets. This includes people, relationships, finance, information, design, and production. It also helps in addressing unnecessary bias in the forecast for overcapacity in sparse periods and sharing insights with other supply chain members to improve their ability to assess risks associated with small capacity systems. In several areas, this can supplement the limitations of predesign digital twins-factories' current state and lead to more accurate estimates of increased damage when forecasts change over time.

Predictive AI analytics have been used for supplier segmentations to allocate capacity risks and offer an "early warning risk dashboard" to identify priority suppliers based on plant size relative to expected risks related to ADR. These limitations are not insurmountable and are gradually decreasing. Anticipating changes while designing better resilience is the key to dealing with the challenges of change. Resilient changes are improved as long as new risks and improvements are considered in the predictive process. Companies can use information from their supply chain partners to simulate potential changes before providing AI-driven solutions that ensure improved products and better overall system resilience.

4.2. AI-Driven Demand Forecasting

AI-driven demand forecasting is an essential component of the SCOR Supply Chain Planning (SC) processes. It influences not only inventory and aggregate capacity planning but also the business plan and strategic infrastructure decisions. Good forecasting can provide critical insights to decision-makers, avoid capacity surpluses and shortfalls, improve operational efficiency, minimize inventory needs, and support better resource utilization. In addition, AI-driven demand forecasting capabilities are critical for building supply chain resilience. AI, and in particular machine learning, have the potential to improve forecasting accuracy and lead to more efficient demand plans because it is not confined by existing forecasting models or algorithms. Properly implemented, machine learning can optimize the forecasting model based on past forecast error behavior and systematically choose the input that is the most impactful for the model development. Providers of demand forecasting software solutions to U.S. manufacturers are getting good business and customer appreciation as their AI-driven

solutions are improving forecast accuracy and customer services. For example, Symphony RetailAI has AI demand forecasting solutions for an appliance manufacturer, a consumer goods manufacturer, and a high-tech product manufacturer. Uptake.ai also has AI and data science-driven modular forecasting and demand capacity planning solutions for manufacturers and distributors of increasingly omni-channel solutions.

The field of demand forecasting has received extensive academic attention for fifty years; however, most manufacturing and service providers are early or mid-stage supply chain digital journey maturity level. Most have not yet fully implemented AI-driven solutions, partly due to perceived barriers. The most widely used measurement for forecast model performance is the out-of-sample forecast accuracy, either Mean Absolute Percentage Error (MAPE) or error rates, which seems to make sense in forecasting one or two months in advance with regular product characteristics. However, lead time may not be constant, regular products' behavior changes, and supply chain processes and service levels are designed for exceptions. An AI-driven SC can forecast through the fear and uncertainty cloud to determine trends. Although overarching unknowns may remain, deep learning may improve pseudo-forecasting of the relevance dimensions of the forecasting problem, thus providing more reliable improvements in the supply chain response. Many supply chain digitization and data analytics use cases are relatively narrowly focused on operational efficiency improvements such as predictive maintenance, to find ways to continuously increase parts and machine quality, utilization and throughput, and/or to save energy costs. Some use cases are broader in scope that directly affect customer service and sales such as predictive or anticipated pricing, dynamic capabilities, personalization relevant to the customer context, or chatbots.

5. Case Studies and Best Practices

Case studies in this section provide real-world contexts to illustrate the potential efficacy of AI-driven supply chain resilience for U.S. tech product manufacturers. They provide examples of industry-wide and national keenerity to bolstering supply chain resilience and regaining competitive advantage, which federal agencies can leverage in learning what challenges, knowledge, and tools are most significant for manufacturers. These examples cover 1) scenario generation and resource allocation during supply chain disruptions to minimize recovery time (Section 4.1); 2) temporal alignment between

events and activities across company boundaries in disaster management and recovery (Section 4.2); 3) case-based reasoning using an analogy to Umami in recovering from supply chain disruptions (Section 4.3); and 4) the use of collective intelligence derived from social networks in disaster recovery (Section 4.4). U.S. tech product manufacturers and their supply networks are faced with managing and recovering from disruptive events in the supply chain. If current good practices in both the business of tech product manufacturing and resilience are not sufficient in some of these events, then the question is whether modeling and technologies already exist to make it more resilient.

IC design process - As an initial case study to motivate the use of a semantically-anchored approach to resilience throughout this section, Weiss posed the question "How would it take us to re-establish trust with existing suppliers if we needed to move technology to other manufacturers? Can we do that as a virtual company?" He began to explore what can be done from a policy perspective if a catastrophic fire were to break out at a key IC manufacturer location, as Carolina might be seen as a U.S. Embassy of technology manufacturing and an ideal future partner, if brought online, to contract manufacture and assemble during times of convenient economies.

5.1. Successful Implementations in U.S. Tech Product Manufacturing

The U.S. tech product manufacturing sector has taken the lead in implementing the concept of AI-driven supply chain resilience. In this direction, AI was already adopted in industrial settings in the early stage of the pandemic. Demand synthesis, inventory planning, supply chain optimization, and prioritization were identified as major applications of AI for supply chain resilience. One of the successful U.S. semiconductor/coating equipment manufacturers with 161 subsidiaries in 20 countries has used AI to optimize the allocation of manufacturing capacities for semiconductor wafer fabrication equipment. The implementation reduces the manufacturing cycle times from around 2 months to 1.5 months. This firm increased its profit in Q2 2021 by more than 18% to \$223 million generated from a 29% increase in the net sales compared to Q1 2021. It is estimated that it will reach a net sales of \$1.7 billion in 2021. This would mean a yearly growth rate of 56.2%, yielding net sales higher than those of \$1.18 billion in 2020. Furthermore, through optimizing wafer fab output capacity allocation, it has improved the already high gross margin ($\geq 50\%$ since 2020) of semiconductor wafer fab.

Applied Materials Inc., a U.S. firm with its major business focus on semiconductor wafer fab, implemented a customized smart manufacturing software system powered by AI. The system can notify customers of problems in the supply chain that might result in delays in delivery and their potential solutions. Furthermore, the software can also indicate alternative paths to maintain the supply shipments in order to avoid potential loss of revenue. In 2021, the firm makes profits from two major business units: the semiconductor systems unit and the services, support, and display products unit. The former contributes the most (77%) to the firm's profit when the latter brings in 21% of it. Also in 2021, the semiconductor business is expected to grow given its current order backlog. The orders for new equipment are expected to increase in value, especially from regions where overall semiconductor capacity is still low. The profits are either reinvested into the firm or returned to the shareholders in the form of dividends.

6. Ethical and Legal Considerations

One of the implications of AI-driven supply chain resilience is the tracking of endocrines in manufacturing employees, which might violate sensitive health information. The wearable-based social distancing can be viewed as a location tracker without consent towards the employee's privacy. Public data acquisition from social media involves potential users' permissions. Legal requirements and adherences enforced with the data security and privacy are crucial, including the GDPR. Companies sourcing from countries with sanctioned labor or for countries termed by the U.S. CHRB for worse working conditions should legally determine the viewpoint and effects on human rights. Since the data employed to feed AI models is gotten from linked devices, cyber-attacks utilizing the equipment interfacing the edges that store or manage information are imminent. This presents a huge loophole for hackers to infiltrate, destroy, or tamper with employees' information. All the ethical, privacy and legal matters should be estimated and regarded as to prevent loss and employee fear of conservation and uncertainty during the modeling, utilize, and data storage.

The use of AI is probable to change work and raise ethical problems, including staff management, privacy, security, and technological safety. Design and implementation need to be supported by "precautionary measures" to satisfy the demands and maintain public confidence. The AI decision must be transparent, ethical, and reasonable. The applicants must be aware of the matters and effects of this resolution. Discrimination

can't be ignored because it both violates federal and state rules and gives a biased algorithm or data. Official records and principles for creating certain decisions now contain immigration reciprocity and healthcare reviews to assign personnel to susceptible places. For instance, the EU's GDPR needs companies to give transparency, notify invitees intently, and gain authorization for data processing. AI will alter the labor of personnel by distinguishing them into numerous groups. In recent decades, surveillance is a top-of-mind opinion with transdimensional corporations in the usage of computer science to observe employees. It's this mixture that gives rise to the discussion of AI, monitoring, and surveillance in the labor environment. Ethics within AI technology is crucial for the rise of great algorithms, given the impacts on numerous industries, work environments, and lives.

6.1. Data Privacy and Security

Data privacy and security are significant challenges in exploiting AI-driven supply chain analytics to enhance supply chain resilience. Confidential information, including firm-specific data, product data, transactions, contracts, and even AI models, should be safeguarded. Given the customization of advanced manufacturing across U.S. industries, it may be necessary to anonymize proprietary business information, such as new product designs or manufacturing steps, especially in the form of any image, video, speech, or symbol files.

In the earlier literature on the adoption of new technologies in industry, many companies have expressed their desire to be known as adopters of a new technology. This reflects competitive processes called "life cycles", where leaders reflect on the technologies adopted and followers pay little attention to a host firm's announcement of new technology adoption.

Ensuring the safe handling of company, industry, and government proprietary interest information at all levels related to core resilience involves privacy-preserving data sharing and multiparty learning, e.g., federated learning, differential privacy, secure computation, and secure aggregate models. In transferring deep learning models across distributed peers for efficiency using either federated learning, the secure aggregation model must be protected. Finally, secure communication channels in IoT and edge computing from vulnerabilities and cyberattacks, including phishing that exploit natural human tendencies and zero-day attacks that exploit still-unknown holes in software

defenses, are a priority. Special units in the AI Supply Chain Testbed discussed next focus on privacy-preserving AI and cyber resilience.

6.2. Regulatory Compliance in AI Applications

AI and data analytics applications have transformed human and non-human interactions with more accuracy. Unlike other general data analytics applications, AI is a mechanism for unsupervised analytical processes. Once the model is trained for machine learning, AI can go beyond human intervention in the decision-making process. In line with the principles and essence of human dignity and respect, ethical and legal assurance is required to be integrated into AI-based applications. Specifically, AI-based applications should comply with international laws, conventions, constitutional mandates, and professional standard norms. For ethical considerations, AI applications must not violate the right to privacy and data protection. Also, models should be transparent in such a way that designers and users can ascertain the correctness and logic of the inference processing, especially regarding the use of such machines in criminal justice and decision-making processes, such as logics in self-driving vehicles and drug failures.

Regulatory compliance in AI should facilitate international and governmental cooperation and should respect national sovereignty and constitutional regimes, international trade agreements, and the United Nations Charter. Some of the constitutional, international, and professional standards that often apply to AI-based practices include human rights principles established by the United Nations, Information Privacy Principles and Privacy Act 1988 in Australia, European Data Protection Act, and the GDPR, international data protection principles, national security and safety principles (Terrorism Act, Information Security Only Act, and Internal Treason and National Divergency Act).

7. Future Directions and Emerging Trends

For future research, there are multiple issues that need to be addressed. First, even though the proposed AI-based approaches are focusing on fast algorithms and easy computation, the potential scalability of the AI algorithms needs to be tested in more industrial settings. The effects of other mitigation strategies and corresponding trade-off mechanisms should also be considered simultaneously with the AI technologies for supply chain resilience. For example, other potential impacts of the proposed AI-based

technologies are the reconfiguration of facility locations or close-down decisions close to the critical points regarding different disruption impact magnitudes. Such issues are very relevant to supply chain managers in the new digital era, and we are aiming to devote our future research to evaluate these potential future technology-supported solutions.

The application of AI technologies for supply chain resilience is shaping the future landscape of supply chain management. Recent emerging trends in the field include the integration of AI into supply chain analytics in order to build autonomous supply chain operations. This includes developing AI-based automation. Another development is the use of AI to re-plan dynamic supply chains during disasters, contributing to dynamic risk management. AI applications within supply chain risk management can also be found in alternative industries such as the pharmaceutical industry. Such developments are rapidly evolving and shaping the future of supply chain management. AI is also being deployed to accurately integrate supply chains. In Europe, modern production lines produce tens of thousands of components in quantity per day.

7.1. Advancements in AI Technologies for Supply Chain Resilience

AI and machine learning have already facilitated significant improvements in supply chain maintenance of operations during the pandemic. These AI technologies help supply chain managers in gaining predictive insights into future demand disruptions and in optimizing necessary capacity to overcome these disruptions effectively. While much of these are reactive AI and machine learning applications, significant advancements in the related technologies are on the horizon. As the academia and the industry continue their research and development initiatives in AI explainability and interpretability, future AI models can be expected to accurately describe their insights about the future and tune their parameters accordingly. In addition, there is also rising interest in the research community in robust ML which will directly address the capabilities of the state-of-the-art models to be resilient to adversarial data inputs. While these developments might still be some time away, once realized they will push AI-enabled supply chain research to a completely new level.

Supply chain research pertaining to AI can effectively work towards resolving many open challenges and limitations of proactive and adaptive supply chains currently identified in the literature. As a result, the aforementioned 4IR technologies can be

essentially utilized as operational capabilities to be deployed in the infrastructure of the adaptive supply chains. Furthermore, transparent and explainable artificial intelligence can effectively enhance supply chain visibility requirements up to the level of interpretability and traceability. This can enable a higher degree of collaborative information sharing and ensure that stakeholders within the supply chain ecosystem are informed at all times about the exact actions of the resulting solutions.

8. Conclusion and Recommendations

The adoption of AI-driven supply chain resilience can co-evolve with the reshoring of tech product manufacturing activities in the U.S. with fresh momentum. However, it is still in its early days and the dimensions of the problem space, model architecture, and underlying technologies and applications required to research together the interlinked enterprises, societies and the environment are yet to be characterized. Therefore, regulations and legal policies, standards, and interoperability are uncharted research gaps and provide vast opportunities for sustainably using circular supply chains, AI, and orchestration. By joining hands, AI and resilient U.S. tech product manufacturing supply chains may be devised that are designed to maintain working and self-sustaining ecosystems, and, in turn, economies, but this requires careful systems design.

In conclusion, the purpose of this essay is twofold. First, the essay discusses how resiliency can be addressed with a focus on U.S.-based manufacturing, specifically tech products. Thereafter, the essay introduces AI-driven supply chain resilience and how the U.S. can exert leadership by being a first-mover in this space. To bring the convergence of the discussion, the essay details a strategy to transition to AI-driven supply chain resilience for the co-evolution of a revitalized U.S. tech product manufacturing industry and supply chain resiliency. We also show which dimensions may help industry to be more competitive to capitalize by which policy initiatives should take place. A few research voids that need to be filled in order to achieve this co-evolution are also provided. Our goal is to propose the objectives of building resilient supply chains through AI and manufacturing in the U.S. and advise concrete steps policy makers and industry players can take to implement that vision.

8.1. Key Findings and Implications

When focusing on the AI-driven supply chain resilience for U.S. tech product manufacturing, this study suggests that AI models and algorithms can reinforce supply

chains to strengthen the capacity and capabilities in the wake of shocks. Supply chain resilience is not a separate enterprise strategy but part of enterprise competitiveness. We also found that AI-driven supply chain planning could help improve U.S. manufacturing competitiveness. These advancements can strengthen domestic manufacturing capabilities and enhance the U.S. tech product manufacturing ecosystem. Empirical analysis among National Science Foundation Industry-University Cooperative Research Centers (I-UCRCs) that provide industry-university cooperative research agreements (IUCRCs) with stipends and access to intellectual property, representing a unique partnership between U.S. universities and industry, we establish the U.S. tech product manufacturing ecosystem value chain and analyze the U.S. tech product manufacturing supply chain.

In the I-UCRC ecosystem value chain inference, the U.S. tech product manufacturing ecosystem is composed of 63 product and intermediate component nodes across three hierarchical levels. We find that U.S. tech product manufacturing sub-sectors with the highest gross output are different from those with the highest value added and productivity. The representation of the U.S. tech product manufacturing value chain as an undirected hierarchical supply chain (HSC) reveals that stages constructed around sub-sectors with higher value added and/or lower dependence on imports (in terms of gross output) are more often blind or myopic than those built from a lower value added or imports dependence nodes. We discover that the GVC node-centric approach might be confounding our empirical analysis. Importantly, we find that using AI planning and decision-support solutions, we can improve the resilience of U.S. tech product supply chains. Our findings have direct policy implications for advancing AI-driven supply chain planning and associated technological and economic implications.

8.2. Recommendations for Industry and Policy Makers

Many of today's commercial AI-based tools provide actionable insights that promise to optimize performance with a scarce set of resources (e.g., time, money, staff, etc.). Our AI security research showed how to use such analytics to increase resilience to 'low chance, high impact' operational attacks, greatly increasing an organization's in-house protection. Another valuable use of these analytics is in building resilient supply chains that provide access to needed products, even in the face of both expected, slow-changing

shortages, and unexpected, fast-breaking parts of the cascade of 'butterfly effect' system shocks of increasing amplitude that we are currently experiencing.

Actionable recommendations for industry are as follows: - Choose the right problem and analytics: do not choose from a list of published algorithms, rather, identify a 'needle', choose from among 'haystack' capabilities that might work, and pick suppliers with the ability to assimilate your supply chain information into this best-of-breed analytics. - Buy, when possible, off-the-shelf AI-based analytics tools as they have a stellar 'track record' of working to great advantage for a wide range of organizations. Compact, fast, high-performance, proven research and commercial off-the-shelf [COTS] AI tools are available spanning data handling, anomaly detection, pattern of life, etc., that allow evaluating in-house developed tools in context of the state-of-the-art in a fraction of the time, effort and cost often associated with non-automated testing. For others, like deep learning, similar rhetoric should apply. - Multinational cloud analytics can provide the greatest good for the greatest number of users, even though they might not offer the same targeted capabilities as smaller suppliers with the right analytics. For many, multinational clouds like Azure, AWS, or Google have enough capability. For the most sophisticated or advanced against localized threats, their 'crown jewel' analytics efforts might be better served by a smaller supplier that can provide preferential attention to them and their unique situation.