Proactive Disruption Intelligence and Inventory Hedging Models: AI-Enhanced Supply Chain Resilience Frameworks for U.S. Manufacturing Competitiveness

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1. Introduction, Global manufacturing systems, comprised of inter-linked networks of entities involved in manufacturing-related product and service activities, are becoming increasingly complex. The interdependencies among supply chain nodes can exacerbate the propagation of disruptions, influencing the resilience of manufacturing systems. Deep learning-based predictive models together with game-theoretic contract design can improve the sustainability and resilience of the U.S. manufacturing ecosystem [1]. The representative suppliers and manufacturers (SMs) that establish contracts to exchange parts and components within the supply chain network are modeled as players in repeated non-cooperative games. A new equilibrium and a new optimal contract are both designed to accommodate the influences of uncertainty sources through corrective payoffs. Massive numerical experiments are performed to substantiate the advantage of reasoning for reliability before contracts. Methods also explore AI-enhanced supply chain risk mitigation strategies that boost reputation, resilience, and sustainability.

Academic researchers and industry practitioners have increasingly paid attention to how AI affects risk assessment (RA) in the supply chain (SC) field and have proposed various AI innovations that can efficiently identify and evaluate risks in the SC. However, a comprehensive review of traditional methodologies and AI innovations is currently lacking. A full range of AI techniques is analyzed together with related applications. A novel and sophisticated bibliometric framework is provided to analyze the thematic evolution and research network of AI- SC RA literature [2]. Management issues, implementation challenges, and future research directions of AI in supporting SC RA are also discussed.

1.1. Background and Rationale

U.S. manufacturers are rethinking their sourcing decisions in the wake of significant disruptions to global supply chains and the realization that having everything sourced from faraway places may not be such a good idea. Policy initiatives from federal and state governments, such as the CHIPS act and a new Michigan initiative, are underway to at least partially bring offshored industries back home. The tremendous challenges that the disruptions caused to American manufacturing industries underscored the need for more robust and resilient manufacturing supply chain networks [2]. There is great hope that artificial intelligence (AI) techniques can help monitor socio-political and natural events that can interfere with supply chain operations, forecast the implications of such events, and recommend and even autonomously execute mitigation strategies.

Many diverse industries, including healthcare, finance, and transportation, face similar challenges. In general, new technologies that blend and integrate AI techniques with information technologies for data collection, transmission, and storage and information management technologies for the creation of data-driven digital twins of the physical environment are being used for overall resiliency enhancement. Such technologies are expected to help organizations better anticipate, prepare for, respond to, and recover from disruptive events, uncertainties, and risks [1]. However, these advances in supply chain resilience enhancement have been slow to arrive at the doorstep of U.S. manufacturers.

1.2. Research Objectives

The goals and aims of the research will be addressed in this section. The list of objectives will steer the essay. It will stay on track and help evaluate whether the goal has been attained [2]. Generally, there are three objectives to be met:

1. To identify and discuss the role of artificial intelligence on supply chain resilience. 2. To explore key techniques and applications of artificial intelligence in supply chain resilience. 3. To discuss several case studies on major applications of artificial intelligence in supply chain resilience. 4. To provide an overview of the ethical, legal, and regulatory issues related to artificial intelligence applications of supply chain resilience.

2. The Role of AI in Supply Chain Resilience

AI has emerged as the most dominant technology in supply chain management. Many business leaders believe that artificial intelligence (AI) will have a greater impact than big data, cloud, or social media [1]. It has the potential to remedy several inefficiencies in supply chains. AI algorithms can process much larger amounts of data much faster than traditional statistical tools, delivering better insights in real-time. Thus, there is a natural fit between AI capabilities and the modern infrastructures that companies deploy today.

Conceptually, AI deals with analyzing big datasets using machine learning (ML) algorithms, forming models, and applying these models to improve processes or make forecasts. These models can consider complex relationships between underlying parameters that cannot be modeled with traditional statistical approaches.

Adaptive Artificial Intelligence (AAI) in supply chain risk assessment (SCRA) has garnered attention as a robust solution to identify, analyze, and mitigate risks. A Systematic literature review (SLR) focused on AAI methods enhances the understanding of their current applications in SCRA while addressing existing gaps [2]. The distinction between AI and AAI for SCRA is illustrated. Current AAI applications in SCRA are reviewed, highlighting methods employed, their effectiveness, and areas for future research.

2.1. Definition and Conceptual Framework

A clearly articulated definition of artificial intelligence (AI) is paramount for establishing a common understanding and direction across North American sectors. Initially, a synopsis of the overarching background is presented, segmented into three components, broad formulations showcasing the various branches of academic inquiry, and particular matter on specific concepts. An argument is then made to supplicate the case that an amalgamation of various fields and ideas is paramount, as a singular perspective is unallowable to comprehend and address the prevailing challenges. This background osmosis is addressed to both those who are well-versed and those who are less cognizant about the research and its particular fields. The term artificial intelligence (AI) encompasses a variety of disciplines and methods that seek to animate machines and computer programs with some facets of intelligence also possessed by humans and higher animals [1]. Some common branches are: 1. The Darwinian approach (evolutionary computing) 2. The genetic approach (genetic algorithms/science) 3. The neural networks' approach (connectionism) 4. The cybernetic approach (expert systems, fuzzy logic) 5. The phenomenological approach (natural language processing, robotics, sensors, screen vision) 6. The model-free approach (knowledge base systems, search).

Supply Chain Resilience: A Need for More Apt Mathematical and Artificial Intelligence Algorithms

The historic picture that emerged from the Supply Chain Resilience (SCR) workshop in Washington DC, in October 2104, displays a chain, aka a supply chain, which is a commercial system of seven different links. Each member of the chain has the right and duty to invest in appropriate SCR solutions, either circular or collaborative. Regardless of whether the supply chain is manufactured or service, the research talk results in a need for further development of scientific knowledge and practical experience within some newly recognized links. It foregrounds an urge for more apt mathematical and Artificial Intelligence (AI) algorithms. This paper addresses only one of such links, namely health. In this context, the supply chain is the health service in a community which distributes care on its inhabitants and visitors [2]. The share of health services that is provided by society around the world is about 80%, while the share of market-oriented health services is about only 20%.

2.2. Benefits and Challenges

Artificial Intelligence (AI) has the potential to enable businesses to become more resilient in the event of unexpected national and global disruptions. It is anticipated that AI will have the most dramatic effects in industries rich in data and information, on which intelligent decisions can be made. There is a growing expectation that this technology can be an enabler of better resilience in supply chains, given the proliferation of data available from connected sensors, smart devices, product identifiers and other sources [1]. This research is a timely and relevant contribution to the growing demand for insights into the increasing threats to the resilience of companies' supply chains. Resilience is an ever-evolving concept. Initially it was used mainly to describe the ability to recover from a disruptive shock or crisis. Over the years this concept has been refined to mean the ability to prepare for, absorb, adapt to and recover from disruption events.

It is critically important for manufacturers to be aware of future events where exposure to risk could grow significantly, and of actions they might take to mitigate these risks. These circumstances may relate to changes in the external market environment such as events which affect customer demand, availability of raw materials or transport infrastructure; changes in competitor activity such as product development, pricing or production capacity; changes in regulations; or changes in internal company policies [2].

3. Key Techniques in AI-Enhanced Supply Chain Resilience

AI and machine learning (ML) have emerged as transformative technologies across various disciplines, including supply chain management (SCM), which have gained increased visibility with the heightened pace of the Fourth Industrial Revolution [3]. As a subfield of AI, ML techniques have been shown to be the driving force behind the exploration of fine-grained sophisticated production practices in a smart manufacturing mindset, as well as the provision of decision-making in real time in manufacturing processes, including supply chain. AI and intelligent technologies should thus be considered important enabling forces to strengthen productivity, quality, efficiency, and sustainability and create value. The COVID-19-induced disruptions in 2020 in global production and logistics systems have demonstrated the vulnerability and lack of resilience of traditional supply chains, and it has become clear that the supply chains can no longer be realigned overnight [2]. Conditions in the global market and econometric variables affecting forecast accuracy keep changing, which adds to uncertainty. Forecasts cannot be made accurately without forecasting models updated continuously, which can only be achieved if the knowledge underlying these models is updated by utilizing the data from the market. Nonetheless, despite the increasing volumes of data available in Industry 4.0, traditional approach systems for supply chain forecasting remain detached from data. Therefore, supply chains must be designed not only to fulfill the requirement of need and demand in real time but also to be modified quickly as a reaction to evolving circumstances.

In a rapidly changing and uncertain environment, manufacturers are increasingly focused on supply chain resilience (SCR) to balance potential trade-offs between firms in a supply chain (SC) both cost-effectively and promptly. Predictive analytics (PA) within the context of supply networks has gained increased visibility among industry communities and academia, and many organizations are adopting PA in their SCs to enhance their competitive advantages. While big data in SCs could help companies monitor any disturbances across the entire SC, predictive analyses could help firms with greater predictive capabilities to better prepare for unforeseeable disruptions rather than just reactively respond to them. As the core of PA, various supervised and unsupervised ML algorithms are gaining steady traction in predicting supply disruptions in prior studies.

3.1. Machine Learning Algorithms

This section delves into the specific machine learning algorithms that play a pivotal role in enhancing supply chain resilience. Machine learning algorithms provide the capability to ingest vast amounts of data and discover complex patterns that inform decision-making. Thus, these algorithms can perform complex analyses on a scale that would be impossible for humans to accomplish. State-of-the-art machine learning algorithms can be broadly categorized into four categories: supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning.

In the context of this discussion, three categories of machine learning algorithms are examined that contribute to the advancement of supply chain resilience. The first category, which includes artificial neural networks and decision trees, is used to create predictive models that inform approaches to prevent risk events or to alleviate their impacts. The second category encompasses clustering methods such as k-means clustering and fuzzy clustering, which are applied to detect risk events through anomaly detection. The third category includes reinforcement learning algorithms that allow a decision-making agent to take actions in an environment to maximize rewards [2]. Such algorithms can be employed to dynamically select supply chain design or operational decisions based on the supply chain's state or disturbances to which it is subjected.

Machine learning techniques are especially useful for creating adaptive and responsive AI-enhanced supply chains, as they can create predictive models of demand, supply, or risk events. Furthermore, machine learning algorithms can automate the continuous monitoring of numerous signals for supply chain disruptions [4]. Data-driven approaches to interpret the outputs of machine learning algorithms and inform decisions have also received significant attention in the literature.

3.2. Predictive Analytics

Predictive Analytics may refer to the proactive measures taken by using forecasting models and techniques to anticipate potential supply chain disruptions, optimize inventory levels, and improve decision-making processes. All supply chains are exposed to disruptions that range from unexpected small suppliers or transportation delays to catastrophic supply chain network breakdowns. A forward-looking approach using predictive analytics may be applied to support the resilience of supply networks against disruptions. Performance is predicted for various but uncertain operational decisions that should be made ahead of time in response to possible disruptions. Short-term disruption predictions are taken into account using historical data, expert knowledge, and data mining techniques. Key Performance Indicators (KPIs) that describe performance under uncertainty may be improved. By using predictive models for KPIs, proactive measures can be taken in advance of disruptions to avoid performance reduction and mitigate adverse effects of disruptions. All this information can be integrated to evaluate KPIs at the decision-making level. Predictive KPI models are analytical or statistical models that use historical data to infer the probable value of KPIs ahead of time [5].

4. Applications of AI in U.S. Manufacturing

Smart Manufacturing

U.S. Manufacturing is at the cusp of another revolution due in large part to advances in Sensor, Cyber, and AI technologies. Smart Manufacturing is a vision where all business (e.g., manufacturing, maintenance, logistics) and technical (e.g., machines, tools, sensors, measurements) operations in a supply chain will be transformed by AI techniques, thus greatly enhancing productivity. For example, production units will leverage Artificial Intelligence (AI) technologies for their scheduling, manufacturing execution, monitoring, and control. Therefore, they will serve as “Smart Factories” [1]. Likewise, suppliers, customers, maintenance services, etc., will become “Smart” by leveraging AI technologies for demand forecasting, warehouse management, technical services, etc. Current manufacturing execution and resource management approaches are highly centralized. Efforts to reduce manufacturing cost (e.g., equipment, material) and manufacturing lead time (e.g., tightly scheduled operations, highly controlled execution) make the operations rigid and inflexible. If unexpected events happen, such as increased demand, supply delays, and machine failures, it will take a long time to re-schedule or change the operations. This may result in a large amount of lost sales and penalties. AI technologies and Cyber Physical Systems (CPS) will provide a decentralized environment in which each production resource will hold a representation of itself (i.e., its status, capability, availability, etc.) and the resources in its neighborhood with which it interacts. In this environment, which can be described as a “Smart Manufacturing” or the “Factory of the Future”, all resources will be “Smart Agents” capable of observing their environment, making the reason for the impact of these observations and acting on their own to enhance performance (e.g., efficiency, quality, reliability).

Inventory Optimization

An extensive literature review of the role of AI in catastrophe and risk management was well presented in the study, focusing on the sub-sector tackling pandemics [6]. An important line of future research, still in the very initial stage, involves the application of AI techniques for predictive analytics of contagious diseases driving preventive measures such as quarantine. Further research is desirable to develop sophisticated AI approaches for alternative scenario modeling as well as for the early-stage detection of contagions. AI (Machine Learning) algorithms have gained momentum in analyzing newswire texts as catalysts for price changes in industries and financial markets. Further research addressing the application of AI approaches for analyzing the influence of social media feeds on manufacturing systems would benefit the sub-sector Supply Chain Optimization. Nowadays, social networks advocate tweets and user-generated posts providing supervisors with a continuous, up-to-date flow of relevant information channelizing the emergence of warning signs in the analyzed process. Hence, forecasting and anticipating events (risks) and noxious impacts over firm performance (the emergence of accidents) leads to the design of sensitivity analyses and stress testing of models (indicators) to be captured ahead of time, before affecting operation and performance results.

4.1. Smart Manufacturing

According to U.S. AI market research conducted by McKinsey Office, AI is projected to directly generate trillions of US dollars in economic value in the future. As a high-value-added industry, AI empowers industries with new opportunities for transformation and development. However, 83% of U.S. manufacturers believe that their organizations will be unable to maintain a competitive edge in a fast-changing business environment when AI-based applications are widely deployed [7]. In the post-pandemic era, manufacturing global value chains were significantly disrupted due to trade wars, increased transportation costs, labor shortages, and supply chain shocks. Smart manufacturing empowered by AI technology is a proactive solution to improve supply chain resilience and boost U.S. manufacturing competitiveness rapidly. Smart manufacturing has been regarded as the main approach for manufacturing industries in the U.S. to address future challenges in a rapidly changing and competitive environment.

Smart manufacturing technologies and applications using AI have transformed U.S. industries. AI-assisted machine vision quality inspection technologies have been adopted in smart manufacturing to reduce defect rates and improve labor efficiency in electronics and automotive manufacturing. Smart manufacturing systems automatically track, analyze, and control production activities in real time using AI techniques, such as the Industrial Internet of Things (IIoT), big data analytics, and system-level models. IoT has been adopted in equipment and production systems for monitoring, dataset collection, and associated analysis using AI technologies. These tasks can discover valuable knowledge by building model counterparts of manufacturing processes and providing manufacturing resources dynamically. AI-enhanced online prediction and root cause diagnosis techniques can significantly reduce energy costs, emissions, and defect rates [8].

4.2. Inventory Optimization

In the U.S. manufacturing sector, AI-enhanced supply chain resilience applications can mitigate revenue losses by accelerating the recovery from shocks and disruptions faced by the supply chain. AI techniques relevant to each of the six resilience applications are explored, including token design, decentralized finance (DeFi), AI-based approaches to supplier selection and liquidity management, and supply chain demand-supply matching. The design of an open-sourced supply chain resilience master plan to ease deployment obstacles and foster collaboration within the supply chain ecosystem for faster resilience is introduced. The plan consists of four parts: resilience maturity assessment, action plan development, resilience solution deployments, and resilience solution monitoring and feedback integration [1].

A sub-framework of AI techniques suitable to overcome obstacles within each application part of the resilience master plan is provided, covering the broad range of AI techniques available, such as natural language processing, machine learning forecasting/design methods, and reinforcement learning. Demonstrator use cases across various real-world supply chain sectors, such as the semiconductor or automotive supply chains, highlight the power of the resilience master plan and AI techniques to improve supply chain recovery and performance amid disruptions [9].

5. Case Studies and Success Stories

This section focuses on case studies and real-world success stories regarding AI's role in boosting supply chain resilience in manufacturing, with a specific view of the domestic U.S. context. These case studies can be industry specific and are aimed at illustrating a broad enough view of how AI may actively change the resilience/competitiveness landscape for manufacturing.

U.S. manufacturing has fallen short in its digital transformation compared to the big players like China and Germany. Many manufacturing companies, especially small and medium-sized enterprises (SMEs), still rely on ubiquitous business software and traditional working practices. This negatively affects their agility, flexibility, and ability to use data intelligently to develop data-based products and services. The digital transformation of supply chains often is the initial step of the overall digital transformation, and it has become essential to secure data in production systems and the digitization of their supply chain too. In the new era of big data and AI, data-driven intelligence is a game-changer for manufacturing companies. Advanced AI and big-data technologies can enhance agility and flexibility at all supply chain levels with fast, precise, and automated decisions [1].

5.1. Industry Examples

An overview of the U.S. manufacturing industry segments was presented above. In moving forward, this section will go into greater detail examining specific industry examples. These industry examples describe how certain manufacturing companies have integrated AI, or advanced analytics, into their supply chain workflows to develop a robust resilience to common concerning disruptions.

The pharmaceutical industry uses AI technology to accelerate the production of a COVID-19 vaccine by simulating the prediction of possible protein folds amid heightened demand related to the pandemic fallout [1]. This refocused design cycle has been pivotal for the pharmaceutical industry in general, whereby the time from computer design to lab creation can be measured in months instead of years. AI searching techniques generate candidate designs that can use molecular modeling setups at a much broader range than would be feasible in human designs. This AI exploration of protein sequence space begins with a target protein structure and suggests amino acid sequences, based on the design environment of chemistry and sequence mutation statistics, that are most likely to fold into the protein's target structure. The COVID-19 vaccine search deal illustrates the practical need for these methods as well as the effectiveness of AI-designed laboratory tests and feedback.

The financial service industry uses AI technology for credit card transactions to pinpoint fraudulent purchases, alerting users before significant damage occurs [2]. AI excels at identifying subtle trends in the spending behavior of millions of daily purchases, stratifying normal spending activities while analyzing thousands of payments in real time to catch fraudulent activities. Financial institutions are both improving their detection models by injecting them into their databases and creating systems for an entire transaction history.

6. Ethical and Legal Implications of AI in Supply Chain Management

Ethics and accountability are becoming fully fledged areas of concern in both AI research and implementation, with specific emphasis on risks and ramifications associated with algorithmic discrimination or bias, privacy and data protection considerations, and the ethical and legal questions as to how the accountability gap that seems to exacerbate reliance on AI technologies might be bridged. Concerns regarding AI ethics and safety are diverse — ranging from worries about a wide range of AI applications being exploited for malicious purposes; to fears of the catastrophic effects of AI scenarios in which a super intelligent AI outperforms humans; to questions on whether AI technology could ever be developed ethically in the first place [1].

With the convergence of various technological advances — including machine learning — the general pace of the development of AI has very much increased, fuelling fears regarding the potential social and economic impact of AI technologies. Early studies warned of a dystopian future in which humanity faces mass unemployment due to the rapid advances and the industrialization of AI. Even though these scenarios are overly pessimistic, examining the ethical and legal accountability of the data-related risks and challenges that are likely to come with the development of AI systems is timely [6].

Supply Chain Management (SCM) is widely regarded as the backbone of competition in manufacturing. Closely related to the principles of Lean Manufacturing and the concept of Value Chain, SCM comprises the management of the end-to-end flow of products, services, and information from the point of origin to the point of consumption. SCM links key business areas and process such as New Product Development, Marketing, Purchasing, Production, Distribution or Customer Services, and facilitates coordination between the network of channel partners.

7. Future Directions and Emerging Trends

Future directions and emerging trends will be presented in the area of AI-enhanced supply chain (SC) resilience, to boost U.S. manufacturing competitors. Artificial Intelligence (AI) is one of the key technologies allowing the automation and reshaping of many previously human-led decisions across the SC. The domain of SC is especially interesting for the applicability of AI technologies, as classic SC optimization already heavily relies on historical data. Furthermore, SCs are large networks of various stakeholders each producing its own datasets. The larger heuristics, number of decisions to optimize, and SCs being composed of numerous local decision makers offer ample opportunity for success, but many uncertainties exist at several decision levels [1]. AI/ML (artificial intelligence/machine learning) techniques have evolved supply chain risk assessment (SCRA) to revolutionize predictive capabilities in identifying, analyzing, assessing, and mitigating risks. To this end, recent advances in AI/ML models, such as Random Forest, XGBoost, and hybrids, have significantly improved precision within SCRA [2]. Emerging trends in AI-enhanced SC resilience will be present and focused on the U.S. manufacturers' needs in automating enterprise-wide decision-level investment portfolios.

8. Conclusion and Summary

The rapid development of Artificial Intelligence (AI) techniques, such as Industry 4.0, Machine Learning (ML), and Deep Learning (DL), along with accompanying big data application infrastructure advancement, has enabled emerging opportunities for supply chain (SC) process improvement. The natural evolution of these techniques is predictive analytics, which utilizes historical data to anticipate what will happen in the future and is currently the focus for many SC applications. This essay presented AI-enhanced SC resilience approaches related to SC disruptions, focusing on vulnerabilities, modeling, and mitigation strategies. Some AI techniques and their applications were highlighted after a brief introduction. Considering the criticality of SC resilience in transforming the U.S. manufacturing landscape to more flexible SC architecture, a priority could be the development of improved experimental methodologies, test beds, and/or pilot studies for the new AI resilience techniques. In addition, more accurate recommended mitigation strategies could be made if the AI vulnerability measures were combined with other metrics identifying SC characteristics, such as SC7E, and external factors (e.g., hub and node characteristics). There remains an opportunity to pursue innovative hybrid AI resilience methodology combinations, such as joining Vulnerability Measures and Modeling and Mitigation Strategies. Finally, to enhance robustness and practical application, attention to data, training, and validation methodology questions is equally valid across all AI techniques.

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