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Enhancing Supply Chain Resilience Through Artificial Intelligence: Developing a Comprehensive Conceptual Framework for AI Implementation and Supply Chain Optimization

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Abstract: *Background*: Amid growing global uncertainty and increasingly complex disruptions, the ability of supply chains to rapidly adapt and recover is critical. The incorporation of artificial intelligence (AI) into supply chain management represents a transformative strategy for enhancing resilience. By harnessing advanced AI technologies, such as machine learning, predictive analytics, and real-time data processing, organizations can more effectively anticipate, respond to, and recover from disruptions.AI improves demand forecasting accuracy, optimizes inventory management, and increases real-time visibility across the supply chain, reducing the risks of stockouts and surplus inventory. Furthermore, I-driven automation and robotics enhance operational efficiency by minimizing human error and streamlining processes. *Methodology/Approach*: This paper proposes a conceptual framework for strengthening supply chain resilience through AI integration. The framework leverages AI technologies to improve key aspects of supply chain resilience, including risk management, operational efficiency, and real-time visibility. *Result/Conclusion*: Additionally, it underscores the importance of collaborative relationships with supply chain partners, enabled by AI-powered data-sharing and communication tools that foster trust and coordination within the network. *Originality/Value*: This comprehensive framework offers a strategic approach to integrating AI into supply chain management, highlighting its potential to significantly enhance resilience, operational efficiency, and sustainability, thereby empowering organizations to navigate the complexities of modern supply chains more effectively.

Keywords: artificial intelligence technologies; conceptual framework; mixed-methods approach; supply chain resilience

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1. Introduction

The modern global economy is interconnected and changes quickly, making supply chains more susceptible than ever to a variety of disturbances. Thus, ensuring supply chain resilience which is the ability to anticipate, prepare for, and respond to such disruptions has become a critical focus for businesses seeking to maintain continuity and competitiveness [1]. According to a recent study published by The Business Continuity Institute (BCI) in an annual supply chain resilience report, 70% of companies have experienced significant supply chain disruptions over the past five years, leading to substantial financial losses and decreased customer satisfaction. This statistic underscores the importance of supply chain resilience and the urgent need to adopt advanced technologies like AI to mitigate these risks.

Artificial intelligence (AI) presents a game-changing opportunity to improve supply chain resilience. AI technologies, including machine learning, predictive analytics, and the

Internet of Things (IoT), enable risk prediction, operational optimization, and accelerated recovery from disruptions [2]. By utilizing AI, businesses can enhance their decision-making procedures, obtain a better understanding of their supply chain operations, and preserve their competitive advantage in the face of uncertainty. The integration of AI technologies with organizational change management processes is a significant gap in the literature on supply chain resilience and AI use. While supply chain resilience can be improved using AI technologies, the management of the organizational changes necessary for an effective AI adoption is not well covered by existing frameworks.

This article explores the integration of AI into supply chain management, presenting a conceptual model illustrating how AI can be embedded at various stages of the supply chain. It investigates the practical strategies and benefits of deploying AI-driven solutions, such as risk identification, supplier management, real-time monitoring, and recovery. Additionally, this discussion covers critical considerations for successful AI implementation in supply chain operations, including data quality, scalability, and cybersecurity. This paper is organized into three main sections. Section 2 discusses the research background. In Section 3, we present a guideline for the supply chain resilience framework. This section covers the identification of the key components of a framework, the creation of AI-driven resilience dimensions, and a discussion exploring the theoretical contribution of the proposed framework as well as its application to a real case. In the same section, we also discuss the limitations and challenges related to the integration of AI technologies. Finally, Section 4 provides the conclusion and future directions in the field.

The motivation for this research stems from a critical gap in the current literature on the integration of AI technologies in supply chain resilience. While extensive research has explored the individual applications of AI, there has been limited investigation into how these technologies can be holistically integrated to enhance overall supply chain resilience. This gap is significant because, in practice, supply chains face complex and multifaceted challenges that require a coordinated approach to AI adoption. Furthermore, the current literature often overlooks the organizational and human factors that affect the successful implementation of AI, such as change management, customization, and real-time adaptability.

The novelty of this research lies in its comprehensive approach, combining the technological, organizational, and human factors into a single framework to provide actionable insights for enhancing supply chain resilience. Addressing this gap is crucial because it offers a holistic view of how AI can be effectively leveraged to improve supply chain resilience in a real-world context. By integrating diverse AI technologies and addressing the accompanying organizational challenges, this research provides a more practical and applicable solution for businesses looking to enhance their resilience against disruptions. The framework's ability to adapt to various industries and operational scales adds value, making it relevant to various supply chain contexts.

2. Background

2.1. Resilience Theory in Supply Chains

In today's world and its globally integrated economy, supply chain resilience is important for companies trying to stay open and competitive in the face of numerous disruptions. The vulnerabilities in the traditional supply chain models have been highlighted by the rising frequency and intensity of catastrophes, like pandemics, natural disasters, and geopolitical conflicts [3]. Consequently, there is an increasing need to create supply chain systems that are more resilient, flexible, and intelligent so they can endure shocks and bounce back quickly. Supply chain resilience refers to the ability of a supply chain to anticipate, prepare for, respond to, and recover from unexpected disruptions. Resilience is essential for maintaining supply chain continuity and ensuring that businesses can withstand and adapt to shocks. Recent events, such as the COVID-19 pandemic, have underscored the importance of resilient supply chains. The ability of a supply chain to foresee, adjust, and react to disturbances, while preserving operational continuity and competitiveness, is referred to as supply chain resilience. Resistance and recovery are the two primary facets of this process. Recovery is the ability to quickly resume normal operations following a disturbance, whereas resistance is the capacity to withstand disruptions with little to no damage [4].

The AI-driven resilience dimensions include flexibility, redundancy, visibility, collaboration, and adaptability [1]. Flexibility refers to the ability of a supply chain to respond to changes in the demand and supply conditions without significant cost increases or delays. Redundancy involves maintaining an excess capacity or alternative sources of supply to ensure continued operation during the disruption [5]. Visibility entails the real-time monitoring of supply chain activities, allowing for the early detection of potential issues and swift corrective actions [6]. Collaboration emphasizes the importance of strong partnerships and communication among supply chain stakeholders to coordinate responses and share resources effectively [7]. Adaptability is the capability to learn from previous disruptions and continuously improve the processes and strategies to enhance resilience [8]. By integrating these dimensions, organizations can build more robust and resilient supply chains that are better equipped to handle the complexities and uncertainties of the modern global market.

Research and development in the field of resilient supply chain started in 2011–2012, with a few publications stemming from a conference mainly focusing on process resilience and sectors' responses. A substantial number of studies have been conducted in the field of resilience in the last few years, especially on digitalization and pandemics.

A literature review has been conducted to understand the current research on supply chain resilience as well as future opportunities for study. Supply chain disruptions have received considerable attention in the literature in recent years, but resilience has been largely ignored [2].

2.2. Resilience vs. Risk Management

Resilience is dynamic and distinct from that of conventional risk management. Risk analysis methods have been a significant part of business decision-making since the 1970s, particularly when paired with financial models [9]. In actuality, risk management comprises analyzing every scenario that could arise from a project or procedure, and then balancing the investment's possible risks and profits (Carter 1972). COSO (2004), the Committee of Sponsoring Organizations of the Treadway Commission, is the foremost authority on enterprise risk management.

Risk management and supply chain resilience are deeply interconnected concepts, with effective risk management serving as the foundation for a resilient supply chain. By proactively managing risks and continuously adapting to the changing environment, companies can build supply chains that not only survive disruptions but also thrive in the face of challenges. The authors of [10] examine ways to combine risk management strategies with supply chain risk management programs that cover supply, products, demand, and information management.

2.3. Key Factors Impacting Supply Chain Resilience

The integration of artificial intelligence (AI) with supply chain management has yielded significant results, enhancing various aspects of supply chain resilience. One of the most notable outcomes is the improvement in demand forecasting accuracy. By leveraging machine learning algorithms and historical data, AI enables more precise predictions of future demand, thereby optimizing the inventory levels and reducing the instances of stockouts [11]. Additionally, collaborative relationships significantly enhance supply chain resilience by fostering better communication, trust, and mutual support among the supply chain partners. When companies collaborate closely with their suppliers, customers, and logistics providers, they are better positioned to share critical information and resources, which helps in identifying and mitigating risks more effectively. For instance, shared data on inventory levels, demand forecasts, and transportation schedules enable all the parties to respond swiftly to disruptions, thereby minimizing downtime and maintaining continuity [12].

The importance of technological innovations has been addressed from different supply chain perspectives. For instance, digital business ecosystems may be a powerful means of increasing supply chain resilience. The authors of [13] argue that when companies combine supply chain processes with digital technologies to enhance resilience, they develop a competitive edge, making DER (Distributed Energy Resources) critical for success; "to strategically compete at the service, product or supply chain level and indeed just survive, companies must use the latest technological advances" [14]. The authors of [2] claim that due to the recent emergence of digital technologies, now is the prime time to conduct research on managing supply chain vulnerabilities, disruptions, and risks, while enhancing visibility [15].

The literature on technological innovations in supply chain resilience began to peak in 2016, establishing the groundwork for new concepts, such as network orchestration and the Internet of Things (IoT) [16]. Herein, the main focus is on how different technologies, such as the IoT, satellite imagery, and blockchain technologies, have either been implemented or may enhance Supply Chain Resilience (SCR).

The reviewed literature has highlighted that collaboration between organizations in the supply chain helps to connect them and represents a holistic approach to the SCRs at various levels (organizational, inter-organizational, network, and the supply chain). This helps in reducing the uncertainties related to absorptive capacity and corporate governance during crises and disruptions and enables or disables organizational learning-cum-innovation. This promotes visibility, velocity, flexibility, and responsiveness in managing the risks associated with consumer demands, supplies, and energy, capital, and financial markets that enable social, environmental, and industrial sustainability. Shared Module values, investments in sustainable SCR practices, and the trust of third-party partners could improve the supply chain partners' performance and the SCR based on social and environmental factors. These are also valuable resources that improve the short-, medium- and long-term responsiveness of supply chain partners.

The literature broadens the context of SCRs to include social networks that bind organizations, promote collaboration between firms in the supply chain, and develop accelerated response and risk recovery capabilities [17]. The literature also emphasizes the role of organizational resilience (OR) in smoothing the remaining ripple effects of disruptions and uncertainties in the organization, networks, and supply chains, and references the sustainable SCR (supply chain resilience) of industrial firms that focus on several dimensions of strategic management [18]. This highlights the need for SCR researchers and practitioners to use service-dominant logic to guide organizational culture, relational governance, and value co-creation in sustainable operations and supply chain management for risk mitigation.

2.4. Overview of AI Technologies

Key AI technologies significantly enhance supply chain operations through their specialized capabilities. Machine learning (ML) is a cornerstone technology in modern supply chains, leveraging predictive analytics and anomaly detection to enhance operations [19]. The predictive analytics, powered by ML algorithms, analyze historical data to forecast future outcomes, such as the demand, inventory levels, and potential disruptions. This proactive approach eliminates uncertainties and aids in effective planning. Furthermore, anomaly detection helps identify unusual patterns that could indicate fraud, quality control issues, or deviations from the expected performance, ensuring smooth and reliable supply chain operations [20].

Natural language processing (NLP) plays a crucial role for harnessing unstructured data, analyzing sources like social media and customer reviews to forecast demand trends accurately. Through demand sensing, NLP techniques analyze information from social media, news, and customer reviews to detect the emerging trends and sentiments. This insight is invaluable for accurate demand forecasting and successful product launches. Additionally, NLP-powered chatbots and virtual assistants streamline communication within the supply chain, handling customer service, order tracking, and supplier queries efficiently, thereby enhancing the overall communication flow [21]. Computer vision significantly improves quality control and inventory management within supply chains. Quality control systems equipped with computer vision inspect products for defects during manufacturing, ensuring that quality standards are consistently met and reducing waste and recalls. In inventory management, computer vision provides the real-time tracking of inventory levels, offering precise data for better control and restocking processes, ultimately optimizing inventory management [22].

Robotic process automation (RPA) automates repetitive tasks, increasing efficiency and reducing errors. In order processing, RPA handles tasks such as order entry, invoice processing, and data entry, which traditionally require significant manual effort. This automation not only speeds up these processes but also eliminates human errors. Furthermore, RPA continuously monitors supply chain activities, delivering real-time alerts and updates on shipment statuses, inventory levels, and production schedules, thereby enhancing overall supply chain monitoring [23].

Blockchain technology enhances transparency and traceability in supply chains through its decentralized ledger system. This technology records transactions in a secure, immutable manner, ensuring that all parties can verify the authenticity of products and preventing fraud. Smart contracts, another application of blockchain, automate and enforce contractual agreements, reducing the need for intermediaries and ensuring timely payments and deliveries, which streamline supply chain operations [24].

The Internet of Things (IoT) transforms asset tracking and predictive maintenance within supply chains. IoT devices provide real-time data on the location and condition of goods in transit, monitoring factors like temperature and humidity to ensure optimal shipment conditions. In predictive maintenance, IoT sensors continuously assess equipment health, predicting maintenance needs before failures occur. This proactive maintenance approach reduces downtime and extends the lifespan of machinery, thereby maintaining uninterrupted supply chain operations [25].

These AI technologies collectively enhance the efficiency, accuracy, and resilience of supply chains, enabling better decision-making, reducing operational costs, and improving customer satisfaction.

2.5. Role of Artificial Intelligence in Supply Chain Resilience

A supply chain risk assessment defines and prioritizes the risks within the supply chain. The main objective of a supply chain risk assessment is to evaluate the probability and materialization of specific risks and their impacts [26]. In order to increase the resilience of the supply chain, it is advised that companies build alternative relationships, make different decisions, and employ alternative or parallel processes. In this vein, the strategic use of artificial intelligence has been promoted. Supply chain risk management (SCRM) aims to eliminate disruptions, predict their impact, and learn from previous experiences [27].

Management is of particular importance when assessing the potential development of risks within the supply chain. In addition to the strategic risk categories, which are the price, demand, and supplier, a strategic risk assessment also includes inventory, manufacturing, and market evaluations. These represent the business model, the global supply chain, and resiliency. AI and machine learning are the most commonly mentioned techniques in the literature, as they are powerful tools for various data source analytics [27]. see Table 1.

Table 2 should provide a clearer and more engaging understanding of how different AI technologies contribute to supply chain resilience, supported by real-world examples and references.

Table 1. Contributions and case studies of AI technologies on Supply Chain Resilience.

AI Technologies	Contribution to Supply Chain Resilience	Example and Case Studies	References
Machine Learning	-Risk Prediction: Predicts potential disruptions by analyzing historical data and identifying patterns. -Demand Forecasting: Improves accuracy in forecasting demand, reducing overstock and stockouts.	- Amazon: Uses machine learning for demand forecasting, resulting in optimized inventory levels and reduced costs. - Walmart: Predicts store specific demand, improving supply chain efficiency.	[11] Supply Chain Risk Management: Advanced Tools, Models, and Developments.Springer.
Predictive Analytics	-Operational Optimization: Enhances decision-making by providing insights into future trends and performance. Proactive Risk -Management: Identifies potential risks and recommends mitigation strategies before disruptions occur.	- Procter and Gamble: Uses predictive analytics to optimize supply chain operations, reducing lead times and improving service levels.	[28] Big data analytics in logistics and supply chain management: Certain investigations for research and applications. International Journal of Production Economics.
Internet of Things (IoT)	- Real-Time Monitoring: Provides real-time visibility into supply chain operations, allowing for quick response to disruptions. - Asset Tracking: Monitors the condition and location of goods, reducing losses and ensuring timely delivery.	- Maersk: Uses IoT for realtime tracking of shipping containers, improving logistics and reducing delays. - Coca-Cola: Monitors vending machines and supply levels in real-time.	[11]
Robotics and Automation	- Operational Efficiency: Automates repetitive tasks, reducing human error and increasing speed and efficiency. - Flexible Manufacturing: Enables adaptive manufacturing processes that can quickly respond to changes in demand or supply chain disruptions.	- Siemens: Uses robotics for flexible manufacturing systems, enhancing Production efficiency and resilience. - Zara: Automates inventory management, reducing lead times and improving accuracy.	[27,29]
Blockchain	- Transparency and Traceability: Ensures secure and transparent recording of transactions, improving traceability of products. - Fraud Prevention: Reduces the risk of fraud and counterfeiting by providing immutable records of all transactions.	- IBM Food Trust: Uses blockchain to track food supply chains, improving traceability and reducing the risk of foodborne illnesses. - De Beers: Tracks diamonds from mine to retail, ensuring authenticity.	[3,30]
Natural Language Processing (NLP)	-Automates customer service interactions, improving response times and customer satisfaction. - Supplier Communication: Analyzes supplier communications to identify potential issues and areas for improvement.	- Amazon Alexa: Uses NLP to improve customer service and supply chain inquiries. - Unilever: Analyzes supplier contracts and communications to enhance supplier management.	[11,31]

Table 2. Key components of framework.

Component	Description	Category	References
Automation and Robotics	Incorporates AI-driven automation in warehouses and logistics to increase efficiency, reduce human error, and enhance operational resilience.	AI Technologies	[30,32]
Risk Management and Mitigation	Uses AI to predict and manage risks by analyzing various data sources and identifying potential supply chain vulnerabilities and threats.	Supply Chain Resilience Dimensions	[3,32]
Supply Chain Optimization	Applies AI to optimize routing, transportation, and logistics, thereby reducing costs and improving delivery times.	Supply Chain Elements	[11,30]
Supplier Relationship Management	Enhances collaboration with suppliers through AI-driven insights and automated communication, improving reliability and partnership strength.	Supply Chain Elements	[3,31]
Scenario Planning and Simulation	Uses AI to model various scenarios and simulate their impacts on the supply chain, aiding in strategic planning and decision-making.	Supply Chain Resilience Dimensions	[3,30]
Customer Service Enhancement	Employs AI to improve customer interactions through chatbots and automated support, ensuring better services and more satisfaction.	Supply Chain Elements	[11,31]
Sustainability and Compliance	Monitors and ensures compliance with regulations and sustainability goals through AI-driven tracking and reporting.	Supply Chain Resilience Dimensions	[3,32]
Integration with Legacy Systems	Facilitates the integration of AI technologies with existing IT infrastructure, ensuring seamless operations and data flow	Supply Chain Elements	[30]

3. Conceptual Model of AI in Supply Chain Resilience

A conceptual framework of AI and resilience integration involves understanding the multifaceted roles AI can play in enhancing the agility, robustness, and responsiveness of supply chains. This framework aims to delineate the various AI applications, identify the key performance indicators for assessing resilience, and outline strategic pathways for effective implementation [30]. By systematically exploring these elements, businesses can harness the full potential of AI to create more resilient and adaptive supply chains that are capable of thriving in an increasingly uncertain environment [33].

The purpose of this research is to develop a comprehensive conceptual framework that integrates multiple AI technologies to enhance supply chain resilience. This framework will provide guidance on the effective implementation of AI tools, addressing both technical and organizational aspects to ensure a holistic approach to resilience. To address the identified gap, this study focuses on four key research questions that explore different dimensions of integrating AI into supply chain resilience. These questions are designed to guide the development of a comprehensive conceptual framework and provide actionable insights for practitioners. The proposed research questions are as follows:

1. How can multiple AI technologies be integrated to create a cohesive solution for supply chain resilience?

2. What organizational and human factors must be considered to successfully implement AI technologies in supply chains?
3. What are the long-term impacts and sustainability considerations of implementing AI technologies in supply chains?
4. How can the proposed framework be adapted to different industries and supply chain contexts?

3.1. Process of Developing a Conceptual Framework

Developing a conceptual framework for enhancing supply chain resilience with artificial intelligence (AI) involves several systematic steps, incorporating an extensive literature review, stakeholder engagement, and iterative refinement. These steps are as follows:

- **Stage 1: Literature Review and Theoretical Foundation** Conduct an extensive review of the existing literature on supply chain resilience and AI technologies. This involves identifying the key resilience dimensions, such as flexibility, redundancy, visibility, collaboration, and adaptability [34]. Simultaneously, examine the AI applications in supply chain management, focusing on predictive analytics, real-time monitoring, and decision support systems [11]. This is presented in Section 1.
- **Stage 2: Identify Key Components and Relationships** Based on the literature review, identify the critical components that will form the conceptual framework. These typically include AI technologies, supply chain elements (e.g., procurement, production, and logistics), and resilience dimensions [3]. Establish the relationships between these components, such as how AI technologies can enhance specific resilience dimensions.
- **Stage 3: Framework Development** Develop the initial conceptual framework by integrating the identified components and relationships. This involves mapping out how different AI technologies can be applied at various stages of the supply chain to improve resilience. For example, machine learning is used for demand forecasting to enhance flexibility, and real-time data analytics are used for improved visibility [35]. Engage with industry experts, academics, and supply chain professionals to validate the framework. This can involve interviews, workshops, or Delphi studies to gather feedback and insights on the practical applicability and robustness of the framework [36].
- **Stage 4: Refinement and Iteration** Incorporate the feedback from the expert consultation phase to refine and improve the framework. This iterative process ensures that the framework is comprehensive and applicable to real-world scenarios [37].
- **Stage 5: Case Studies and Empirical Testing** Apply the conceptual framework to case studies or conduct empirical research to test its validity and effectiveness. This step involves collecting data from organizations that have implemented AI technologies in their supply chains and analyzing the impact on resilience [38].
- **Stage6: Finalization and Documentation** Finalize the conceptual framework based on the results of empirical testing and case studies. Document the development process, including the theoretical foundation, framework components, validation steps, and empirical findings, to provide a comprehensive guide for practitioners and researchers [39].

3.2. Key Components and Relationships

3.2.1. Key Compenents

Formulating a conceptual framework for supply chain resilience through AI technologies entails delineating the essential elements, connections, and procedures that allow AI to augment supply chains' resilience and flexibility [Table 2].

The selected components of the conceptual framework are justified based on their direct impact on key resilience factors: agility, robustness, and visibility. Each AI technology contributes uniquely to enhancing these factors, leading to overall improved supply chain resilience. The framework can be further refined by exploring additional AI technologies and resilience factors, as well as by incorporating the industry-specific considerations and longitudinal studies to assess long-term impacts.

The conceptual framework for this study integrates key artificial intelligence (AI) technologies with the critical resilience factors of supply chains: agility, robustness, and visibility. The conceptual framework of this study is designed to address various facets of supply chain resilience through a comprehensive integration of advanced AI technologies and strategic management practices.

Automation and robotics are central to this framework, as they streamline repetitive tasks and enhance operational efficiency, directly impacting supply chain optimization and agility. Risk management and mitigation are critical components, focusing on identifying potential risks and implementing strategies to reduce their impact, thus strengthening supply chain robustness. Supply chain optimization leverages AI to improve resource allocation, reduce costs, and enhance overall performance, ensuring that supply chains can respond effectively to market changes. Supplier relationship management is incorporated to emphasize the importance of fostering strong relationships with suppliers, which is essential for maintaining stability and ensuring the timely delivery of goods. Scenario planning and simulation are included to facilitate preparedness for various potential disruptions, enabling supply chains to devise and test response strategies in a controlled environment. Customer service enhancement through AI-driven tools ensures that customer needs are met promptly and accurately, improving overall satisfaction and loyalty. Sustainability and compliance are vital to ensuring that supply chain practices align with environmental regulations and ethical standards, which is increasingly important in modern supply chains. Finally, integration with legacy systems is addressed to highlight the need for seamless connectivity between new AI technologies and the existing infrastructure, ensuring that technological advancements do not disrupt current operations but rather enhance them. By incorporating these components, the framework provides a holistic approach to enhancing supply chain resilience, ensuring that each aspect—from operational efficiency and risk management to customer satisfaction and regulatory compliance—is effectively addressed.

3.2.2. Theoretical Foundations for AI-Driven Supply Chain Resilience

The framework discusses the potential benefits of AI applications such as machine learning, predictive analytics, and the Internet of Things (IoT), but it is essential to anchor the discussion in the Dynamic Capabilities Theory and the Resource-Based View (RBV). According to [40] the Dynamic Capabilities Theory highlights how crucial it is for an organization to be able to integrate, develop, and reconfigure internal and external capabilities in order to deal with quickly changing circumstances. This idea emphasizes the need for businesses to have capacities that allow them to detect disruptions, grasp opportunities, and change their operations in order to preserve their competitive advantage, making it especially pertinent to supply chain resilience. The manuscript can investigate the ways in which AI technologies support the development of dynamic capacities by bringing the suggested framework into line with this notion. Predictive analytics, for instance, may be used to detect changes in the environment, and machine learning may make it possible for supply chain operations to be quickly reconfigured in response to these changes. According to [41] Resource-Based View (RBV), an organization's competitive advantage stems from its capacity to obtain and handle uncommon, precious, unique, and non-replaceable resources. AI technologies can be positioned as strategic resources that satisfy these requirements within the framework that has been suggested. Customized machine learning algorithms for a company's supply chain operations, for example, may be regarded as an uncommon and important asset, offering insights and productivity that rivals find difficult to match. In a similar vein, IoT devices that are thoroughly ingrained in a business's operations may be viewed as non-replaceable assets that improve supply chain visibility and management [1].

3.3. Framework Development

3.3.1. AI Integration in Supply Chain Resilience

The diagram illustrated in Figure 1 is inspired by the comprehensive review and conceptual frameworks discussed in the literature, particularly in Refs. [2,42].

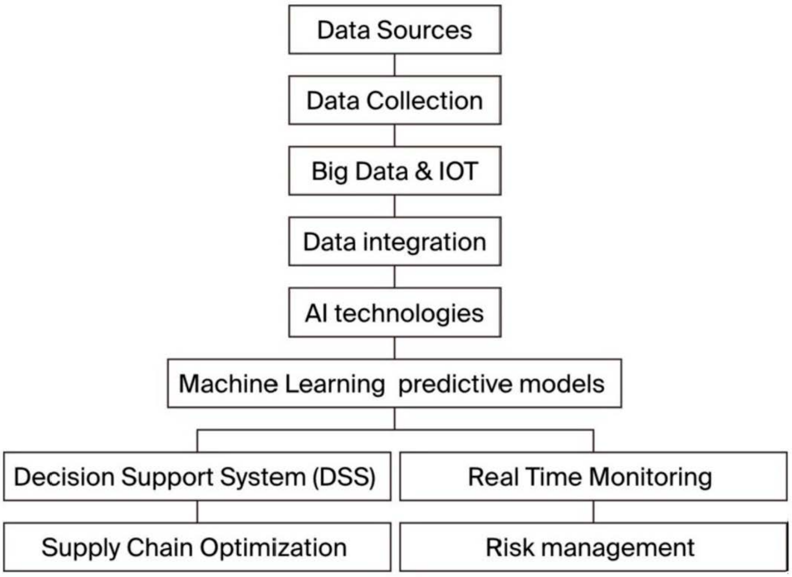

Figure 1. AI supply chain resilience integration process.

Modern supply chains rely on a variety of data sources, including IoT devices, sensors, and ERP systems, to gather comprehensive information across different stages of the supply chain. The data collection process involves aggregating this information, which is then managed using big data technologies to handle the large volumes and provide real-time insights. Data integration and preprocessing are crucial steps to ensure that the collected data are clean and consistent, making them ready for analysis. AI technologies, such as machine learning models and predictive analytics, play a vital role in analyzing these data, offering valuable insights for decision-making. Decision support systems (DSSs) further aid in making informed choices by providing recommendations and forecasts. Real-time monitoring and visibility ensure that supply chain data are accessible and transparent, allowing for quick responses to any disruptions. Through AI-driven insights, supply chain optimization can be achieved, improving efficiency and resilience. Additionally, risk management and contingency planning are essential processes that help prepare for potential disruptions, ensuring that the supply chain remains robust and responsive.

3.3.2. AI-Driven Resilience Dimensions

The diagram in Figure 2 is based on [11], focusing on how AI technologies enhance specific resilience dimensions in the supply chain. To delve deeper into each component and their inter-relationships, we conduct a more detailed analysis.

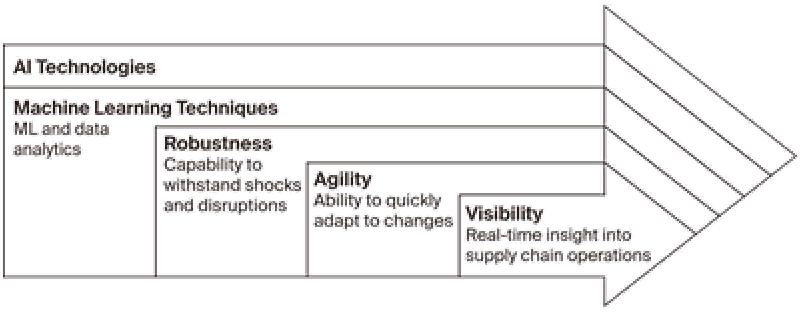

Figure 2. AI-driven resilience dimensions.

Machine learning (ML) enables predictive analytics, anomaly detection, demand forecasting, and pattern recognition, which are crucial for anticipating and mitigating disruptions. However, data analytics involves analyzing large volumes of structured and unstructured data to extract actionable insights that inform decision-making processes [34]. The examples illustrated in the literature are predictive maintenance, in which the ML algorithms predict equipment failures before they occur, thereby minimizing downtime. Also, demand forecasting using data analytics tools involves analyzing historical sales data to predict future demands, ensuring optimal inventory levels.

The agility in supply chain resilience represents a quick response. AI technologies facilitate rapid responses to changes in demand, supply, and other external factors and enable the dynamic adjustment of production schedules, inventory levels, and distribution strategies. AI-powered logistic platforms optimize the delivery routes in real-time based on the traffic conditions, reducing the delivery times and costs. Machine learning algorithms also adjust the inventory levels dynamically to meet the changing demand, eliminating stockouts and overstock situations [6].

AI has an important role in the robustness of the supply chain, which represents its ability to withstand and recover from disruptions by identifying vulnerabilities and implementing risk mitigation strategies. Furthermore, AI helps design robust supply chain networks with alternative suppliers and routes [43]. In the literature, many examples of this have been cited as follows: 1—risk management, in which the AI models assess the likelihood and impact of various risks (e.g., supplier failures and natural disasters) and recommend mitigation strategies; and 2—supplier diversification, where the AI tools evaluate and recommend a diverse set of suppliers to reduce the dependency on a single source [44].

AI technologies provide the real-time visibility of supply chain operations, enhancing decision-making and coordination [3], and traceability through the tracking and tracing of products throughout the supply chain, improving quality control and compliance. IoT devices and AI platforms monitor and report on the status of shipments, inventory levels, and production processes in real-time. Also, blockchain integrates with AI to ensure the secure and transparent tracking of goods from the origin to the destination [45].

3.3.3. AI-Enhanced Supply Chain Resilience

Developing a conceptual framework for AI-based supply chain resilience involves synthesizing the findings from various studies to create a structured model. This framework will highlight the key components, processes, and inter-relationships that collectively contribute to a resilient supply chain. Below is a visual representation of the conceptual framework. see Figure 3.

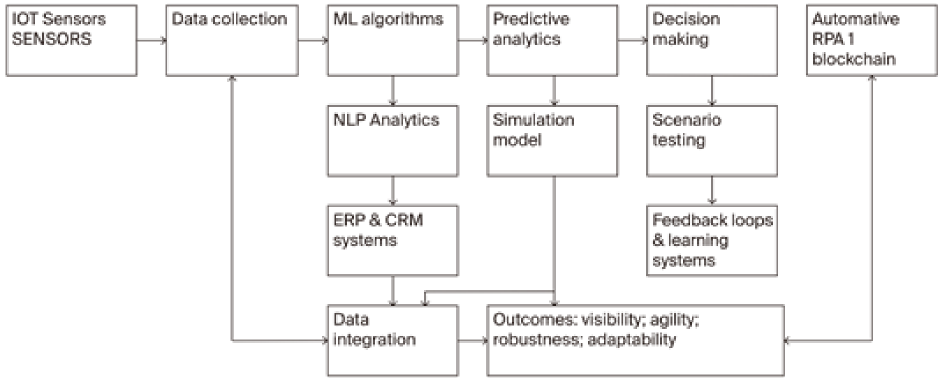

Figure 3. AI-enhanced supply chain resilience framework.

The AI-enhanced supply chain resilience framework is designed to bolster the robustness and agility of supply chains by leveraging advanced AI technologies. At its core, the framework integrates real-time data collection from IoT devices and sensors, providing a centralized repository for comprehensive analysis. Predictive analytics and machine learning algorithms are employed to forecast demand and identify potential risks, such as supplier disruptions or market volatility. This predictive capability allows for proactive risk management and optimized decision-making, particularly in inventory and logistics. AI-driven communication platforms enhance collaboration with suppliers and stakeholders, ensuring transparent and efficient information exchange. Continuous monitoring and feedback loops enable the supply chain to adapt dynamically to changing conditions, fostering an environment of constant improvement and innovation. By implementing this framework, companies can achieve greater supply chain visibility, mitigate risks effectively, and maintain operational continuity even in the face of disruptions, ultimately leading to enhanced supply chain resilience and performance.

The difference between dimensions and factors: Resilience factors like agility, robustness, and visibility are specific attributes that contribute directly to the resilience of a supply chain, while dimensions are broader conceptual categories that organize and integrate these factors to provide a comprehensive view of supply chain resilience. Dimensions help in understanding how different resilience factors interact and contribute to the overall robustness of the supply chain.

3.3.4. Enhancing Supply Chain Resilience with Generative AI

Generative AI enhances supply chain resilience by enabling more advanced predictive analytics, real-time decision-making, and scenario planning. By analyzing vast amounts of data, generative AI can predict potential disruptions and their impacts more accurately, allowing organizations to proactively mitigate risks [6]. It also supports real-time visibility and monitoring across the supply chain, helping to identify bottlenecks and inefficiencies promptly [43]. Furthermore, generative AI can create detailed simulations and what-if scenarios, enabling companies to explore various strategies and their outcomes before implementing them in practice [3]. This capability enhances strategic planning and decision-making during uncertainty, fostering a more agile and adaptable supply chain. Additionally, generative AI enhances collaboration and communication among the supply chain partners by providing data-driven insights and facilitating seamless information sharing [30]. Overall, the integration of generative AI into supply chain management not only strengthens its resilience but also drives operational efficiency and strategic foresight.

Risk management and disruption mitigation are other areas where generative AI also excels. The ability to simulate various scenarios and predict potential risks allows for companies to develop proactive strategies to address these challenges. Whether it is a natural disaster, geopolitical tension, or a pandemic, generative AI can help identify the impacts of such disruptions and suggest effective mitigation strategies. This capability ensures that businesses can maintain continuity and adapt quickly to unforeseen events, enhancing their overall resilience [5].

The optimization of logistics and transportation is another significant benefit of generative AI in supply chains. By analyzing and optimizing routing and scheduling, generative AI ensures the efficient use of resources and minimizes delays. This efficiency is crucial for maintaining the smooth flow of goods and services, especially during disruptions. Improved logistics leads to cost savings and better services, which are essential components of a resilient supply chain [46].

Generative AI also enhances supply chain visibility and transparency. Integrating data from various sources provides real-time insights into the status of shipments, inventory levels, and suppliers' performance. This heightened visibility allows for better decision-making and quicker responses to any issues that arise, ensuring a more robust and adaptable supply chain. Transparency across the supply chain helps in identifying bottlenecks and inefficiencies, enabling continuous improvement and resilience [47].

Collaboration and coordination among supply chain partners are facilitated by generative AI, which provides a platform for sharing information and insights. This improved collaboration leads to a more synchronized supply chain that is capable of adapting swiftly to changes. When the partners are well coordinated, they can respond more effectively to disruptions, maintaining the flow of goods and services. Enhanced collaboration fosters trust and reliability among partners, further strengthening the supply chain's resilience [48].

Generative AI also aids in managing supplier relationships by analyzing their performance and reliability. Analysis helps companies identify the potential risks associated with single-source suppliers and develop strategies for diversification. By ensuring a reliable and diverse supplier base, businesses can mitigate supply chain disruptions and enhance their resilience. A diversified supply chain is less vulnerable to disruptions from any single supplier, thereby improving its overall stability. Sustainability and environmental impacts are becoming increasingly important considerations in developing resilient supply chains. Generative AI can optimize processes to reduce waste and energy consumption, contributing to environmental sustainability. Sustainable supply chains are not only more resilient to regulatory changes but also appeal to environmentally conscious consumers. By incorporating sustainability into supply chain strategies, businesses can achieve long-term resilience and operational efficiency.

3.4. Refinement and Iteration

A conceptual framework's refinement and iteration stage is a crucial one, especially when dealing with dynamic and complicated subjects like supply chain resilience boosted by artificial intelligence. Through ongoing input, empirical testing, and theoretical alignment, this stage focuses on methodically refining and validating the original framework. Through stakeholder engagement, pilot study implementation, and iterative framework development grounded on practical discoveries, this process guarantees that the conceptual model adapts to effectively address real-world difficulties. Because this step is iterative, the framework may be thoroughly tested in a variety of scenarios, improved to solve any flaws found, and tailored to better meet the real-world requirements of varied supply chain settings.

3.4.1. Advancements in Conceptual Understanding

The application of AI-driven technologies in humanitarian supply chains represents a significant theoretical advancement, particularly in the context of Supply Chain 4.0. This paradigm integrates AI with other Industry 4.0 technologies such as Big Data Analytics, IoT, and blockchain to enhance the agility, resilience, and responsiveness of supply chains [49]. The theoretical framework underpinning these advancements emphasizes the role of real-time data processing and predictive analytics in improving decision-making processes. For instance, machine learning models have been developed to optimize demand forecasting and resource allocation, crucial in crisis situations where timely and accurate information is vital [50].

Theoretical contributions include the enhancement of visibility and coordination across supply chain networks, facilitating better response strategies during emergencies [50].

The recent literature highlights the theoretical contributions of AI-driven technologies in enhancing the understanding of supply chain dynamics. This includes the development of new models and frameworks that integrate AI capabilities, such as machine learning, natural language processing, and computer vision, into traditional supply chain theories. These models are increasingly used to anticipate needs in crisis situations, thereby aligning resources more effectively [51].

In fact, the conceptual framework's results coincide with the literature's conclusions, which summarizes that the crucial role of AI in enhancing supply chain resilience is in leveraging data, predictive analytics, optimization, and continuous learning. It aligns with global best practices and the existing literature, providing a comprehensive strategy for businesses to navigate the complexities of modern, interconnected supply chains.

The findings from this study provide significant contributions to several established theories in supply chain management. By integrating advanced AI technologies such as predictive analytics, machine learning, and IoT into the conceptual framework, the study reinforces the Resource-Based View (RBV) by illustrating how technological capabilities can serve as strategic resources that enhance competitive advantage. This integration demonstrates that technological innovations not only streamline operations but also redefine resource management, aligning with the emphasis of the RBV on leveraging unique resources for superior performance. Additionally, the results support the Dynamic Capabilities Theory, highlighting how AI-driven technologies facilitate the development of capabilities essential for adapting to environmental changes and disruptions. The improved agility and robustness achieved through automation and scenario planning exemplify how firms can build dynamic capabilities to navigate complex and evolving market conditions. Furthermore, the findings enrich the supply chain resilience framework by providing empirical evidence on how risk management, supplier relationships, and operational optimization contribute to overall resilience. This study offers new insights into the interplay between these components and how they collectively enhance supply chain robustness. Lastly, the application of automation and robotics resonates with the Theory of Constraints (TOC), demonstrating how technological advancements can effectively address and alleviate bottlenecks in supply chain processes, thereby optimizing throughput and overall performance.

3.4.2. Applications and Real-World Impact

In practical terms, AI-driven technologies have had a transformative impact on humanitarian supply chain operations. The deployment of AI in logistics management, for example, has optimized routing and scheduling, significantly reducing the time and costs associated with delivering aid to affected regions [52]. Additionally, AI-powered systems have improved inventory management by predicting demand patterns and managing stock levels more effectively, ensuring that critical supplies are available when and where they are needed most [50]. Another practical application of AI is in enhancing transparency and accountability within supply chains. The use of blockchain technology, in conjunction with AI, provides a secure and transparent ledger of all transactions, which is particularly important in humanitarian contexts where resource tracking and distribution integrity are crucial [49]. This technology ensures that all stakeholders, from donors to beneficiaries, can verify the flow and usage of resources, thereby building trust and improving overall supply chain governance. Moreover, AI-driven technologies have significantly contributed to the practical aspects of humanitarian supply chains, improving operational efficiency and resource allocation. AI technologies have been used to improve the accuracy of demand forecasts and inventory management, ensuring that supplies are allocated efficiently.

This has been particularly important in responding to sudden-onset disasters where quick decision-making is crucial [53].

In addition, the use of AI in optimizing logistics and transportation routes has led to significant cost savings and more efficient delivery of humanitarian aid. AI algorithms can identify optimal routes and modes of transport, considering various constraints such as road conditions and security concerns [54]. AI-driven platforms facilitate better coordination among various stakeholders, including (on-Governomental-Organisations(NGO), government agencies, and donors. This coordination is essential for the timely and effective distribution of resources in disaster-stricken areas [55].

To address these critical gaps and provide a comprehensive understanding of the proposed framework of the role of AI in enhancing supply chain resilience, the following sections present detailed responses to the research questions, offering insights into the integration of AI technologies, organizational considerations, long-term impacts, and adaptability across different contexts.

By systematically addressing each component of the conceptual framework, we can illustrate how AI plays a crucial role in enhancing supply chain resilience across different contexts.

3.5. Case Study and Empirical Testing

Overall, AI-driven conceptual frameworks are transforming supply chain management by enhancing visibility, optimizing processes, and improving resilience as it is mentioned in such papers in the literature as [56]. AI significantly enhances the impact of agility, visibility, and robustness cited in the previous framework in supply chains by providing advanced tools and capabilities that drive efficiency and resilience. Through its application to Electronics Manufacturing, a world leader in the production of consumer electronics, this case study seeks to empirically test the conceptual framework for AI-enhanced supply chain resilience. Automation and robotics, risk mitigation and management, supply chain optimization, supplier relationship management, scenario planning and simulation, customer service enhancement, sustainability and compliance, and integration with legacy systems are some of the framework's important components. The goal is to assess the ways in which these elements, when combined with AI technology, enhance the overall resilience of the supply chain.

3.5.1. Methodology

The research used a mixed-methods design, integrating quantitative data analysis and qualitative interviews to obtain a thorough grasp of the framework's efficacy. This method makes sure that when assessing the framework, the breadth of the quantitative data as well as the depth of the human experience are taken into account [2]. Twenty senior managers from a variety of departments, including production, customer service, procurement, and logistics, participated in in-depth interviews. The perceived effect of AI technology on supply chain resilience was the main topic of these interviews. Data on operational performance, including delivery delays, stock out rates, production efficiency, and customer happiness before and after AI adoption, were gathered over a 12-month period.

Each section of the questionnaire includes a mix of quantitative and qualitative questions aimed at capturing both measurable outcomes and nuanced perspectives from respondents. This synthesis of the questionnaire not only facilitates the systematic analysis of responses but also enables a comprehensive understanding of the challenges and opportunities associated with AI implementation in supply chains. A summary of the questionnaire is presented below:

1. Which AI technologies does your organization currently use in the supply chain (e.g., AI-driven robotics, predictive analytics, and machine learning for supplier evaluation)?
2. How effective is the integration of multiple AI technologies in improving supply chain resilience? (Rate from 1 = Not Effective to 5 = Highly Effective)

3. What challenges have you encountered when integrating AI technologies into your supply chain (e.g., system compatibility, high costs, skill gaps)?
4. To what extent has integrated AI improved the following?
   - Supply chain visibility.
   - Response time to disruptions.
   - Operational efficiency (Rate each from 1 = Not Improved to 5 = Highly Improved).
5. How prepared is your organization in terms of human resources for AI implementation? (Rate from 1 = Not Prepared to 5 = Very Well Prepared)
6. What organizational changes were needed to implement AI in your supply chain (e.g., staff training, redesign of processes, and leadership changes)?
7. Rank the most important human factors that have influenced AI implementation success:
   - Employee acceptance.
   - Training and skill development.
   - Leadership support.
   - Cross-functional collaboration.
8. Rate the impact of the following organizational factors on AI success:
   - Organizational culture.
   - Communication of AI benefits.
   - Staff engagement (Rate each from 1 = No Impact to 5 = High Impact).
9. What long-term benefits do you anticipate from AI in your supply chain (e.g., operational efficiency, cost reduction, improved decision-making, and sustainability)?
10. What sustainability considerations have been integrated into your AI-driven supply chain (e.g., waste reduction, carbon footprint minimization, and resource efficiency)?
11. Rate the long-term impact of AI on the following:
    - Reducing supply chain costs.
    - Improving environmental sustainability.
    - Enhancing adaptability to market changes (Rate from 1 = No Impact to 5 = High Impact).
12. What challenges do you foresee in maintaining AI for long-term sustainability (e.g., high maintenance costs, need for continuous updates, and technology resistance)?
13. How adaptable is your current AI-driven supply chain framework to different industries? (Rate from 1 = Not Adaptable to 5 = Highly Adaptable).
14. What adjustments would be required to apply your AI framework to a different industry?
15. What factors make AI frameworks more adaptable across various industries (e.g., flexibility in AI algorithms, scalability, and data standardization)?

3.5.2. Results

The case study of the company's qualitative analysis revealed several important issues that highlight the influence of AI technologies on supply chain resilience. AI-driven automation significantly increased production efficiency and reduced errors, according to the managers' consistent reports. This strengthened and depended upon the supply chain. Predictive analytics with AI technologies was emphasized as being essential to spotting and reducing risks before they may affect operations and strengthening the supply chain's overall resilience. Furthermore, the capacity to use AI to model different situations was regarded as a significant benefit that would help the business remain operationally uninterrupted and efficiently plan for any disruptions. Emerging insights from the analysis also pointed to the importance of human factors in the successful implementation of AI technologies. Managers frequently mentioned the need for comprehensive employee training and effective change management strategies, emphasizing that a workforce that is adaptable and skilled in using new technologies is essential for realizing the full benefits of AI in supply chain operations. This underscores the importance of not only investing in AI technologies but also in developing the human capital necessary to leverage these technologies effectively.

In today's complex supply chain environment, understanding the experience levels of key personnel is crucial for enhancing operational efficiency and resilience. This table presents an overview of various roles within the organization, detailing the number of participants in each position and their average years of experience. These data provide insight into the expertise available within the team, which can significantly influence decision-making processes and the successful implementation of strategies aimed at improving supply chain resilience. see Table 3.

Table 3. Characteristics of interviewers.

Position	Number of Participants	Average Years of Experience
Production Manager	5	10
Customer Service Manager	4	8
Procurement Responsible	3	12
Logistics Leader	7	9
IT Manager	1	15

The following table presents a comprehensive synthesis of the questionnaire utilized in this study, detailing the specific components and focus areas of each section. Each part of the questionnaire aligns with the core elements of the conceptual framework, designed to capture essential data on the integration of AI technologies in enhancing supply chain resilience. see Table 4.

The survey results on AI integration in supply chain resilience reveal several important insights into the current state of AI adoption, the challenges faced, and the perceived impacts on various aspects of supply chain operations. First, the data indicate a relatively balanced adoption of AI technologies, with 12 respondents affirming their use of AI in supply chain processes. The most commonly adopted technologies include machine learning, automation, and analytics, suggesting a trend towards leveraging advanced data analysis and process automation to enhance operational efficiency. The evaluation of AI effectiveness shows a predominance of neutral to positive perceptions, with a significant number of respondents rating AI technologies as effective (4 or 5 on a scale of 1 to 5). This highlights the growing recognition of the role of AI in enhancing supply chain resilience, although there remains a minority who view its effectiveness skeptically.

Furthermore, the challenges faced during integration reveal critical areas for improvement. System compatibility emerged as the most significant issue, underscoring the need for better interoperability between existing systems and new AI technologies. Additionally, high costs and a lack of skilled personnel were noted as barriers, indicating a need for investment in both technology and workforce development to facilitate smoother transitions. Interestingly, the majority of respondents believe that AI has improved visibility in the supply chain. This reflects the potential of AI to enhance data transparency and decision-making processes, which are essential for effective supply chain management. The positive feedback on visibility supports the idea that AI can provide real-time insights crucial for anticipating disruptions and improving responsiveness.

The equal split between organizations implementing training for AI and those that have not suggests that many companies may still be underestimating the importance of workforce readiness. The need for organizational changes, particularly in training and process reorganization, highlights the necessity of preparing teams for the digital transformation that AI integration entails. Respondents foresee significant long-term benefits from AI integration, particularly in increased efficiency and cost reduction. This aligns with broader industry trends where organizations seek to streamline operations and drive profitability through advanced technologies. While AI is perceived as beneficial for cost reduction, concerns about sustainability remain. High maintenance costs and the need for continuous updates are highlighted as obstacles. This points to the importance of not only adopting AI but also ensuring that the systems put in place are sustainable and adaptable to evolving regulatory requirements and market conditions. Moreover, the majority of respondents feel that their AI frameworks can adapt to other industries, indicating a potential for cross-industry applications of AI solutions. However, the responses also suggest a need for the customization of algorithms and redefinition of KPIs to ensure that AI tools can be effectively tailored to different contexts. The emphasis on algorithm flexibility, scalability, and standardization reflects a strategic approach to enhancing AI systems' adaptability. Organizations must prioritize these factors to maximize the potential benefits of AI across various supply chain scenarios.

Table 4. Survey results on AI integration in supply chain resilience.

Questions	Responses
Have you adopted AI technologies in your supply chain process?	Yes: 12, No: 8
What are the main AI technologies adopted?	Machine Learning: 5, Automation: 4, Analytics: 3
How do you evaluate the effectiveness of AI technologies for resilience?	1 (Not effective): 2, 2: 4, 3: 6, 4: 5, 5 (Very effective): 3
What challenges have you encountered when integrating AI technologies?	System compatibility: 8, High cost: 6, Lack of skills: 5
Has the integration of AI technologies improved supply chain visibility?	1 (Not improved): 1, 2: 3, 3: 4, 4: 8, 5 (Very improved): 4
Have you implemented training for AI implementation?	Yes: 10, No: 10
What are the main organizational changes needed?	Training: 8, Process reorganization: 6, New governance frameworks: 3
What are the main long-term expected benefits?	Increased efficiency: 9, Cost reduction: 7, Better decision-making: 4
What are the main obstacles to the sustainability of AI technologies?	High maintenance costs: 6, Continuous updates: 5, Resistance to change: 3
How do you evaluate the impact of AI on reducing supply chain costs?	1 (No impact): 2, 2: 3, 3: 6, 4: 5, 5 (Strong impact): 4
How do you evaluate the impact of AI on environmental sustainability?	1 (No impact): 1, 2: 3, 3: 6, 4: 6, 5 (Strong impact): 4
Do you believe your AI framework is adaptable to other industries?	1 (Not adaptable): 1, 2: 3, 3: 7, 4:6, 5 (Very adaptable): 3
What adjustments would be necessary to adapt the AI framework to other industries?	Customization of algorithms: 6, Redefinition of KPIs: 5, Integration of new standards: 3
What factors promote the adaptability of AI frameworks?	Flexibility of algorithms: 7, Scalability: 5, Standardization of processes: 4
Other factors to consider for integrating AI into the supply chain?	Continuous training, Adaptability to future regulations

Overall, the survey results provide valuable insights into the current landscape of AI integration in supply chain resilience. While there is a strong recognition of the benefits AI can bring, challenges related to integration, training, and sustainability must be addressed to fully leverage its potential. The findings also suggest a clear path forward, emphasizing the importance of organizational readiness, workforce training, and a focus on adaptability to ensure successful AI implementation in diverse supply chain contexts.

3.5.3. Discussion of Results

The results of this empirical testing provide strong evidence supporting the efficacy of the conceptual framework in enhancing supply chain resilience at the tested company. The thematic analysis revealed that AI-driven automation and robotics are particularly effective in improving production efficiency and reducing errors, leading to a more resilient supply chain. The use of AI in risk management and scenario planning has also been instrumental in preparing the company for potential disruptions, thereby ensuring operational continuity. However, the success of these implementations is closely tied to human factors, such as employee training and adaptability, which emerged as critical enablers of effective AI adoption. The descriptive statistics indicate high satisfaction levels among employees with the AI components implemented, with mean scores above 4.1 for all components. The correlation analysis shows strong positive relationships between the AI components and supply chain resilience, particularly in customer service enhancement (r = 0.85) and automation and robotics ($r = 0.82$). The regression analysis confirms these components as significant predictors of supply chain resilience, with customer service enhancement showing the highest standardized beta coefficient (β = 0.50). The comparative analysis highlights substantial improvements in key performance indicators following the implementation of AI technologies. The reduction in stockouts from 9% to 2% and the decrease in average delivery time from 8.5 days to 4.2 days demonstrate the tangible benefits of the framework. Additionally, the significant increase in customer satisfaction from 70% to 88% and the boost in production efficiency from 74% to 91% further validate the positive impact of AI-driven initiatives on supply chain performance. This empirical testing of the conceptual framework at the company demonstrates that integrating AI technologies across key supply chain components can significantly enhance resilience. The framework's components, including automation and robotics, risk management, and supply chain optimization, have proven to be effective in improving both operational efficiency and customer satisfaction. These findings not only validate the framework but also offer practical insights for other organizations seeking to enhance their supply chain resilience through AI. Future research could involve longitudinal studies to assess the sustainability of these improvements and explore the framework's applicability in different industries and geographical contexts. This study contributes to the growing body of knowledge on AI-driven supply chain resilience and provides a robust foundation for further exploration and refinement of the conceptual framework.

In order to meet the challenges of organizational and operational transformation, the research questions in this study are designed to give readers a thorough grasp of how artificial intelligence (AI) can be incorporated into supply chains. These inquiries are meant to explore the various facets of AI adoption, from the technological amalgamation of several AI solutions to the more extensive organizational and human elements that impact effective execution. Furthermore, the inquiries delve into the enduring viability of artificial intelligence technologies in supply chains and the ways in which this structure might be modified to suit diverse industry scenarios.

RQ1: How can multiple AI technologies be integrated to create a cohesive solution for supply chain resilience?

AI-driven automation and robotics enhance supply chain resilience by improving efficiency and reducing human error. Automation streamlines repetitive tasks, such as inventory management and order processing, ensuring consistency and speed. Robotics, equipped with AI, can adapt to various tasks in warehousing and manufacturing, handling disruptions swiftly and maintaining operations during labor shortages. This reduces the risk of bottlenecks and delays, enhancing overall resilience.

1. Risk Management and Mitigation AI enhances risk management by providing predictive analytics and real-time monitoring. Machine learning algorithms analyze historical data to forecast potential disruptions and identify emerging risks. AI systems can evaluate various risk factors, such as supplier reliability and geopolitical

events, allowing companies to implement proactive measures. This helps in designing more resilient supply chains by addressing potential issues before they escalate.

2. Supply Chain Optimization AI contributes to supply chain optimization through advanced analytics and decision support systems. It can optimize inventory levels, forecast demand more accurately, and streamline logistics by analyzing data patterns and trends. By enhancing decision-making capabilities and reducing operational inefficiencies, AI ensures that supply chains are more adaptable and responsive to changes, thereby improving resilience.
3. Supplier Relationship Management AI improves supplier relationship management by providing insights into supplier performance and enabling better communication. AI tools can analyze supplier data to identify performance issues, assess risks, and recommend improvements. Enhanced visibility into supplier operations allows for better collaboration and more informed decision-making, which strengthens supplier relationships and contributes to overall supply chain resilience.
4. Scenario Planning and Simulation AI facilitates scenario planning and simulation by using predictive models and simulations to analyze various "what-if" scenarios. AI systems can simulate different disruptions, such as supply shortages or logistical delays, and assess their impact on the supply chain. This enables companies to prepare contingency plans and develop strategies to handle various disruptions, thus enhancing resilience.
5. Customer Service Enhancement AI enhances customer service by enabling more responsive and personalized interactions. AI-powered chatbots and virtual assistants provide real-time support and handle customer inquiries efficiently. Predictive analytics help in anticipating customer needs and optimizing order fulfillment processes. By improving service quality and response times, AI contributes to customer satisfaction and loyalty, which is a critical component of a resilient supply chain.
6. Sustainability and Compliance AI can be integrated with legacy systems through middleware and APIs that facilitate data exchange and process automation. This integration enables legacy systems to benefit from the advanced capabilities of AI without requiring a complete overhaul. By enhancing existing systems with AI, companies can improve data accuracy, streamline operations, and increase resilience, while preserving their investment in legacy infrastructure.

RQ2. What organizational and human factors must be considered to successfully implement AI technologies in supply chains?

Finding the organizational and human elements that affect these technologies' effective adoption is essential as companies work to harness the revolutionary potential of artificial intelligence (AI) in supply chains.

1- Impact of Automation and Robotics on Workforce Dynamics: Investigate how the implementation of automation and robotics affects job roles, skill requirements, and employee attitudes. What training programs are necessary to prepare the workforce for these changes.

2- Risk Management and Mitigation Strategies: Explore how organizational culture and leadership impact the adoption of AI-driven risk management and mitigation practices. What human factors influence the effectiveness of these strategies?

3- Change Management for Integration with Legacy Systems: Examine the challenges organizations face when integrating AI technologies with existing legacy systems. How do human factors such as resistance to change and lack of technical skills affect this integration?

4- Collaboration in Supplier Relationship Management: Analyze the role of cross-functional collaboration in successfully implementing AI in supplier relationship management. How do organizational structures facilitate or hinder this collaboration?

RQ3. What are the long-term impacts and sustainability considerations of implementing AI technologies in supply chains?

Supply chains can benefit greatly from the application of AI technology in terms of increased resilience and efficiency, but responsible and successful integration will also require careful consideration of sustainability issues and long-term effects.

1- Sustainability and Compliance Metrics: Investigate the long-term sustainability impacts of AI technologies in supply chains, focusing on how these technologies help organizations meet compliance requirements and enhance sustainability efforts. What metrics can be developed to assess these impacts?
2- Risk Management for Long-Term Viability: Analyze the long-term economic impacts of AI-driven risk management and mitigation on supply chain resilience. How do these practices contribute to financial stability and sustainability in the long run?
3- Supply Chain Optimization and Resource Efficiency: Explore how AI technologies improve supply chain optimization and resource efficiency, leading to long-term cost savings and reduced environmental impact. What are the measurable benefits of these optimizations?
4- Scenario Planning and Simulation for Future Preparedness: Assess the role of AI-driven scenario planning and simulation in enhancing long-term resilience. How do organizations use these tools to prepare for future disruptions and ensure sustainability?

RQ4: How can the proposed framework be adapted to different industries and supply chain contexts?

The flexibility to modify supply chain strategy becomes essential for success as companies negotiate an ever more dynamic and complex global marketplace. The objective of the suggested framework is to improve supply chain resilience by using creative methods. But depending on the industry and the situation, it might not always be as effective.

1- Customization of AI in Automation and Robotics: Identify industry-specific needs for automation and robotics.
2- Supplier Relationship Management Across Industries: Examine how supplier relationship management practices differ across industries and how the framework can be adapted accordingly.
3- Scenario Planning and Simulation in Various Environments: Analyze how scenario planning and simulation can be customized to fit the diverse operational environments and challenges faced by different industries.
4- Integration with Legacy Systems in Diverse Contexts: Investigate the varying challenges of integrating AI with legacy systems in different industries.

3.6. Finalization and Documentation

From a practical perspective, the results underscore several actionable strategies for organizations aiming to enhance their supply chain operations. First, investing in AI technologies such as predictive analytics and machine learning is crucial for optimizing supply chain processes, improving demand forecasting, and enhancing anomaly detection. Organizations should focus on integrating these AI tools into their existing systems to achieve higher operational efficiency and better decision-making. Additionally, developing robust risk management strategies that incorporate scenario planning and simulation can significantly improve an organization's preparedness for potential disruptions, ensuring more effective risk mitigation. Strengthening supplier relationships through transparent communication and collaborative problem-solving can lead to improved reliability and stability within the supply chain. Organizations are also advised to leverage AI-driven customer service tools to enhance customer satisfaction and loyalty by providing timely and personalized support. Moreover, integrating sustainability and compliance into supply chain practices is essential for meeting regulatory requirements and addressing environmental concerns, which can also bolster brand reputation. Finally, ensuring that new technologies are seamlessly integrated with legacy systems is critical for avoiding disruptions and maximizing technological benefits. By adopting these recommendations, organizations can enhance their supply chain resilience, optimize performance, and achieve a competitive edge in today's dynamic market environment.

The conceptual framework unifies resilience dimensions and several AI technologies in supply chain management, and it applies a lens of analysis to each study subject. Our objective is to offer a thorough comprehension of how the suggested framework improves supply chain resilience by examining the interactions among these constituents. Linking the pertinent elements of the framework to the collected empirical data, the discussion is structured to answer each research topic in turn. We may evaluate the framework's usefulness on a critical level, point out its advantages, and pinpoint areas that require more investigation with this method.

3.7. Research Limitations and Prospective Studies

Despite the significant advancements, several limitations challenge the widespread adoption of AI-driven technologies in humanitarian supply chains. One of the primary challenges is the digital divide, which affects the implementation of advanced technologies in less developed regions that may lack the necessary infrastructure and technical expertise [50]. Furthermore, issues related to data privacy and security are paramount, particularly when dealing with sensitive information in vulnerable communities. One of the primary limitations identified in the literature is the issue of data quality and access. AI-driven technologies rely heavily on large datasets, which can be difficult to obtain in humanitarian contexts due to infrastructure limitations, political instability, and privacy concerns. The variability in data sources and the inconsistency in data quality can lead to unreliable outputs from AI systems. This variability poses a challenge for the deployment of AI technologies in regions with limited technological infrastructure [57].

Future research should address these limitations by developing scalable and adaptable AI solutions that can be applied across diverse settings. There is also a need for further exploration into the ethical implications of AI use in humanitarian contexts, including the potential for bias and the equitable distribution of aid [49]. Additionally, researchers should investigate the integration of AI with other emerging technologies, such as drones and autonomous vehicles, to enhance the efficiency and effectiveness of humanitarian logistics. The integration of AI with other emerging technologies, such as blockchain and IoT, can enhance transparency, traceability, and efficiency in humanitarian supply chains. This convergence could also help address issues related to data integrity and security [58].

The application of AI in humanitarian supply chains raises ethical issues, particularly concerning data privacy and the potential for biased decision-making. There is a need for robust ethical guidelines to govern the use of AI in sensitive contexts. AI systems may inadvertently reinforce existing biases if they are not carefully monitored and adjusted. This issue is particularly critical in humanitarian contexts, where decisions can significantly impact vulnerable populations. Developing comprehensive ethical frameworks to guide the use of AI in humanitarian contexts is crucial. These frameworks should address issues of data privacy, bias, and the equitable distribution of resources.

Generative AI has also a significant potential as a future direction for research in using AI to enhance supply chain resilience. Unlike traditional AI techniques that focus on pattern recognition and optimization, generative AI creates new data, scenarios, and solutions based on learned patterns [59]. This capability can be harnessed in several innovative ways to improve supply chain resilience.

The literature has highlighted significant theoretical and practical contributions of AI-driven technologies in humanitarian supply chains. These technologies have improved decision-making, efficiency, and coordination in delivering humanitarian aid. However, challenges related to data quality, ethical considerations, and scalability remain. Future research should focus on overcoming these limitations and further exploring the integration of AI with other technologies to enhance the overall effectiveness of humanitarian operations.

4. Conclusions and Future Directions

Building a resilient supply chain requires a balanced approach that integrates both resistance and recovery strategies. While resistance focuses on preventing disruptions and maintaining stability, recovery ensures that the supply chain can bounce back quickly from any disruptions that do occur. A well-rounded strategy that combines these elements can significantly enhance the overall resilience of the supply chain. Diversification involves sourcing from multiple regions to reduce dependence on a single supplier or geographic area, thereby mitigating risks associated with supply chain disruptions. This strategy enhances supply chain resilience by ensuring that if one source becomes unavailable, others can continue to supply necessary materials. Inventory management plays a crucial role in this approach by maintaining the strategic reserves of essential items, which serve as a buffer against unexpected supply interruptions. Additionally, risk management and assessment are key components of a resilient supply chain. These processes involve identifying potential hazards, such as natural disasters or geopolitical tensions, and developing strategies to mitigate their impact. Furthermore, the integration of advanced technologies like blockchain, IoT, and AI enhances supply chain responsiveness and transparency. These technologies enable real-time tracking, data analysis, and secure information sharing, which help organizations quickly adapt to changing conditions and maintain operational continuity.

AI plays a pivotal role in enhancing supply chain resilience by providing predictive insights, optimizing operations, improving visibility, and enabling automated decision-making. While there are challenges associated with data integration, including its complexity and ethical concerns, AI can be used to build a resilient supply chain. Future research and the development of AI technologies will continue to drive innovation in supply chain management, helping businesses to navigate and thrive in an increasingly uncertain world.

Integrating generative AI into supply chain management offers numerous benefits, including improved efficiency, transparency, sustainability, and adaptability. By leveraging these advanced technologies, companies can enhance their resilience to disruptions and better navigate the complexities of the global market. The transformative potential of generative AI in supply chains ensures that businesses are well equipped to face future challenges and seize opportunities in an ever-changing environment.

As illustrated in this paper, AI technologies can significantly assist in the forecasting and planning phase during disruption by understanding the customers' needs and by gaining insights from financial and e-commerce analyses. The unstoppable growth in technological capabilities and the current economic conditions are forcing many businesses to rethink and redesign their supply chain resilience frameworks. AI innovations, including the advanced data analytic tools, new data capturing and storage technologies, and new demand planning and forecasting tools discussed in this paper, can enhance supply chain resilience and management. The efficient integration and implementation of these advanced AI tools in a supply chain framework could lead to quicker, smarter, and more environmentally efficient processes that address the consequences of power outages, pandemics, terror attacks, natural disasters, and global recessions, which were all experienced at an unprecedented scale due to the COVID-19 pandemic [60].

In addition to diversification and strategic inventory management, several implementation considerations are critical for enhancing supply chain resilience through AI. First, the integration of high-quality, unified data is essential for the effective deployment of AI technologies. This data foundation ensures accurate analytics and decision-making across the supply chain. Second, AI solutions must be scalable to accommodate the complexity and size of the supply chain, allowing for consistent performance across different levels of operation. Third, fostering human–AI collaboration is vital for balanced decision-making, combining the strengths of the data processing capabilities of AI with human intuition and contextual understanding. Additionally, robust cybersecurity measures are necessary to protect sensitive supply chain data from cyber threats, ensuring the integrity and confidentiality of information. Finally, regulatory compliance must be considered, as adhering to relevant laws and standards is crucial for the lawful and ethical implementation of AI technologies in supply chain operations.

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References

1. Christopher, M.; Lowson, R.; Peck, H. Creating Agile Supply Chains in the Fashion Industry. *Int. J. Retail. Distrib. Manag.* **2004**, *32*, 367–376. [CrossRef]
2. łMin, H. Artificial intelligence in supply chain management: Theory and applications. *Int. J. Logist. Res. Appl.* **2010**, *13*, 13–19. [CrossRef]
3. Ivanov, D.; Dolgui, A.; Sokolov, B. The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *Int. J. Prod. Res.* **2019**, *57*, 829–846. [CrossRef]
4. Mirzaee, H.; Samarghandi, H.; Willoughby, K. On designing a resilient green supply chain to mitigate ripple effect: A two-stage stochastic optimization model. *arXiv* **2023**, arXiv:2303.01729.
5. Sheffi, Y.; Rice, J.B. A supply chain view of the resilient enterprise. *MIT Sloan Manag. Rev.* **2005**, *47*. Available online: https://sloanreview.mit.edu/article/a-supply-chain-view-of-the-resilient-enterprise/ (accessed on 18 September 2024).
6. Planning, P.; Ivanov, D. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Prod. Plan. Control* **2020**, *32*, 775–788. [CrossRef]
7. Jüttner, U.; Maklan, S. Supply chain resilience in the global financial crisis: An empirical study. *Supply Chain Manag.* **2011**, *16*, 246–259. [CrossRef]
8. Ponomarov, S.Y.; Holcomb, M.C. Understanding the concept of supply chain resilience. *Int. J. Logist. Manag.* **2009**, *20*, 124–143. [CrossRef]
9. Hertz, D.B.; Thomas, H. Decision and Risk Analysis in a New Product and Facilities Planning Problem. *Sloan Manag. Rev.* **1983**, *24*, 17–31.
10. Tang, O.; Musa, S.N. Identifying risk issues and research advancements in supply chain risk management. *Int. J. Prod. Econ.* **2011**, *133*, 25–34. [CrossRef]
11. Choi, T.M.; Wallace, S.W.; Wang, Y. Big Data Analytics in Operations Management. *Prod. Oper. Manag.* **2018**, *27*, 1868–1883. [CrossRef]
12. Simatupang, T.; Sridharan, R. The International Journal of Logistics Management Emerald Article: Supply Chain Metrics. *Int. J. Logist. Manag.* **2002**, *13*, 15–30. [CrossRef]
13. Patriarca, R.; Bergström, J.; Gravio, G.D.; Costantino, F. Resilience engineering: Current status of the research and future challenges. *Saf. Sci.* **2018**, *102*, 79–100. [CrossRef]
14. Sengupta, T.; Narayanamurthy, G.; Moser, R.; Pereira, V.; Bhattacharjee, D. Disruptive Technologies for Achieving Supply Chain Resilience in COVID-19 Era: An Implementation Case Study of Satellite Imagery and Blockchain Technologies in Fish Supply Chain. *Inf. Syst. Front.* **2022**, *24*, 1107–1123. [CrossRef]
15. Aliahmadi, A.; Nozari, H.; Ghahremani-Nahr, J.; Szmelter-Jarosz, A. Evaluation of Key Impression of Resilient Supply Chain Based on Artificial Intelligence of Things (AIoT). *J. Fuzzy Ext. Appl.* **2022**, *3*, 201–211. [CrossRef]
16. Iftikhar, A.; Ali, I.; Arslan, A.; Tarba, S. Digital Innovation, Data Analytics, and Supply Chain Resiliency: A Bibliometric-based Systematic Literature Review. *Ann. Oper. Res.* **2024**, *333*, 825–848. [CrossRef]
17. Madhavika, N.; Jayasinghe, N.; Ehalapitiya, S.; Wickramage, T.; Fernando, D.; Jayasinghe, V. Operationalizing resilience through collaboration: The case of Sri Lankan tea supply chain during COVID-19. *Qual Quant* **2023**, *57*, 2981–3018. [CrossRef]
18. Manurung, H.; Yudoko, G.; Okdinawati, L. A conceptual framework of supply chain resilience towards sustainability through a service-dominant logic perspective. *Heliyon* **2023**, *9*, e13901. [CrossRef]
19. Riahi, Y.; Saikouk, T.; Gunasekaran, A.; Badraoui, I. Artificial intelligence applications in supply chain: A descriptive bibliometric analysis and future research directions. *Expert Syst. Appl.* **2021**, *173*, 114702. [CrossRef]
20. Makridakis, S.; Spiliotis, E.; Assimakopoulos, V. Statistical and Machine Learning forecasting methods: Concerns and ways forward. *PLoS ONE* **2018**, *13*, 1–26. [CrossRef]
21. Hang, H.; Chen, Z. How to realize the full potentials of artificial intelligence (AI) in digital economy? A literature review. *J. Digit. Econ.* **2022**, *1*, 180–191. [CrossRef]

22. Talwar, R.; Koury, A. Artificial intelligence—The next frontier in IT security? *Netw. Secur.* **2017**, *2017*, 14–17. [CrossRef]
23. Willcocks, L.; Lacity, M.; Craig, A. Robotic process automation: Strategic transformation lever for global business services? *J. Inf. Technol. Teach. Cases* **2017**, *7*, 17–28. [CrossRef]
24. Saberi, S.; Kouhizadeh, M.; Sarkis, J.; Shen, L. Blockchain technology and its relationships to sustainable supply chain management. *Int. J. Prod. Res.* **2019**, *57*, 2117–2135. [CrossRef]
25. Ben-Daya, M.; Hassini, E.; Bahroun, Z. Internet of things and supply chain management: A literature review. *Int. J. Prod. Res.* **2019**, *57*, 4719–4742. [CrossRef]
26. Naife, S.A.; Saha, A.K.; Mridha, M.F. AI in Supply Chain Risk Assessment: A Systematic Literature Review and Bibliometric Analysis. *arXiv* **2023**, arXiv:2401.10895v2.
27. Xu, L.; Mak, S.; Brintrup, A. International Journal of Production Economics Will bots take over the supply chain? Revisiting agent-based supply chain automation. *Int. J. Prod. Econ.* **2021**, *241*, 108279. [CrossRef]
28. Wang, G.; Gunasekaran, A.; Ngai, E.W.; Papadopoulos, T. Big data analytics in logistics and supply chain management: Certain investigations for research and applications. *Int. J. Prod. Econ.* **2016**, *176*, 98–110. [CrossRef]
29. Lee, J.; Kao, H.-A.; Yang, S. Service innovation and smart analytics for Industry 4.0 and big data environment. *Procedia CIRP* **2014**, *16*, 3–8. [CrossRef]
30. Sanders, N. *Big Data Driven Supply Chain Management: A Framework for Implementing Analytics and Turning Information Into Intelligence*; Pearson Education: London, UK, 2014.
31. McAfee, A.; Brynjolfsson, E. *Machine, Platform, Crowd: Harnessing our Digital Future*; W. W. Norton & Company: New York, NY, USA, 2017.
32. Wamba, S.F.; Akter, S.; Edwards, A. Big data analytics for supply chain management: A literature review and research agenda. *Enterp. Inf. Syst.* **2015**, *9*, 153–177. [CrossRef]
33. Davenport, T.H.; Ronanki, R. Intelligence for the Real World. *Harv. Bus. Rev.* **2018**, *96*, 108–116.
34. Murray, P.W.; Agard, B.; Barajas, M.A. Forecasting supply chain demand by clustering customers. *IFAC-PapersOnLine* **2015**, *28*, 1834–1839. [CrossRef]
35. McAfee, A. *Harnessing Our Digital Future*; MIT Press: Cambridge, MA, USA, 2001; p. 43.
36. Rowe, G.; Wright, G. The Delphi technique as a forecasting tool: Issues and analysis. *Int. J. Forecast.* **1999**, *15*, 353–375. [CrossRef]
37. Voss, C.; Tsikriktsis, N.; Frohlich, M. Case research in operations management. *Int. J. Oper. Prod. Manag.* **2002**, *22*, 195–219. [CrossRef]
38. Yin, R.K. Discovering the future of the case study. Method in evaluation research. *Eval. Pract.* **1994**, *15*, 283–290.
39. Eisenhardt, K.M. Building Theories from Case Study Research Published by: Academy of Management Stable. *Acad. Manag. Rev.* **1989**, *14*, 532–550. [CrossRef]
40. Teece, D.J.; Pisano, G.; Shuen, A. Dynamic capabilities and strategic management. *Strateg. Manag. J.* **1997**, *18*, 509–533. [CrossRef]
41. Barney, J.B. Firm resources and sustained competitive advantage. *J. Manag.* **1991**, *17*, 99–120. [CrossRef]
42. Hosseini, S.; Ivanov, D. Bayesian networks for supply chain risk, resilience and ripple effect analysis: A literature review. *Expert Syst. Appl.* **2020**, *161*, 113649. [CrossRef]
43. Papadopoulos, T.; Gunasekaran, A.; Dubey, R.; Altay, N.; Childe, S.J.; Wamba, S.F. The role of Big Data in explaining disaster resilience in supply chains for sustainability. *J. Clean. Prod.* **2016**, *142*, 1108–1148. [CrossRef]
44. Ivanov, D.; Dolgui, A. Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *Int. J. Prod. Res.* **2020**, 58, 1–12. [CrossRef]
45. Nagorny, K.; Lima-Monteiro, P.; Barata, J.; Colombo, A.W. Big Data Analysis in Smart Manufacturing: A Review. *Int. J. Commun. Netw. Syst. Sci.* **2017**, *10*, 31–58. [CrossRef]
46. Das, D.; Datta, A.; Kumar, P.; Kazancoglu, Y.; Ram, M. Building supply chain resilience in the era of COVID-19: An AHP-DEMATEL approach. *Oper. Manag. Res.* **2022**, *15*, 249–267. [CrossRef]
47. Blackhurst, J.; Dunn, K.S.; Craighead, C.W. An empirically derived framework of global supply resiliency. *J. Bus. Logist.* **2011**, *32*, 374–391. [CrossRef]
48. Kiekintveld, C.; Miller, J.; Jordan, P.R.; Callender, L.F.; Wellman, M.P. Electronic Commerce Research and Applications Forecasting market prices in a supply chain game q. *Electron. Commer. Res. Appl.* **2009**, *8*, 63–77. [CrossRef]
49. Marinagi, C.; Reklitis, P.; Trivellas, P.; Sakas, D. The Impact of Industry 4.0 Technologies on Key Performance Indicators for a Resilient Supply Chain 4.0. *Sustainability* **2023**, *15*, 5185. [CrossRef]
50. Kondraganti, A. Big Data Analytics in Humanitarian and Disaster Operations: A Systematic Review. *arXiv* **2021**, arXiv:2108.09800.
51. Dubey, R.; Luo, Z.; Gunasekaran, A.; Akter, S.; Hazen, B.T.; Douglas, M.A. Big data and predictive analytics in humanitarian supply chains: Enabling visibility and coordination in the presence of swift trust. *Int. J. Logist. Manag.* **2018**, *29*, 485–512. [CrossRef]
52. Michel-Villarreal, R.; Vilalta-Perdomo, E.L.; Canavari, M.; Hingley, M. Resilience and digitalization in short food supply chains: A case study approach. *Sustainability* **2021**, *13*, 5913. [CrossRef]
53. Şimşek, D.; Kutlu, İ.; Şık, B. The Role and Applications of Artificial Intelligence (AI) in Disaster Management. 2024. Available online: https://www.researchgate.net/publication/375488867_The_role_and_applications_of_artificial_intelligence_AI_in_disaster_management (accessed on 18 September 2024). . (Auth :ok) [CrossRef]

54. Atwani, M.; Hlyal, M.; Elalami, J. A Review of Artificial Intelligence applications in Supply Chain. *ITM Web Conf.* **2022**, *46*, 03001. [CrossRef]
55. Nurcahyani, I.; Lee, J.W. Role of machine learning in resource allocation strategy over vehicular networks: A survey. *Sensors* **2021**, *21*, 6542. [CrossRef] [PubMed]
56. Park, A.; Li, H. The effect of blockchain technology on supply chain sustainability performances. *Sustainability* **2021**, *13*, 1726. [CrossRef]
57. Gupta, S.; Altay, N.; Luo, Z. Big data in humanitarian supply chain management: A review and further research directions. *Ann. Oper. Res.* **2019**, *283*, 1153–1173. [CrossRef]
58. Sandner, P.; Gross, J.; Richter, R. Convergence of Blockchain, IoT, and AI. *Front. Blockchain* **2020**, *3*, 522600. [CrossRef]
59. Stilinski, D.; Doris, L.; Frank, L. Leveraging Generative AI for Supply Chain Optimization and Simulation. 2024. Available online: https://easychair.org/publications/preprint/BWsS (accessed on 18 September 2024).
60. Pal, R.; Altay, N. The missing link in disruption management research: Coping. *Oper. Manag. Res.* **2023**, *16*, 433–449. [CrossRef]