AI Applications in Supply Chains: A Survey

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Abstract

This survey provides a comprehensive examination of the integration of artificial intelligence (AI) applications within supply chains, focusing on enhancing logistics, digital transformation, and resilience. It addresses the challenges of technological capability asymmetry and explores AI's role in optimizing logistics operations and digital supply chain transformation. The survey highlights AI's potential to bridge capability gaps, emphasizing the importance of collaboration and trust among supply chain partners. It further analyzes AI-driven strategies for enhancing supply chain resilience, including risk management, disruption prediction, and recovery. The integration of AI with digital transformation is shown to bolster resilience, offering advanced predictive capabilities and improved decision-making processes. Case studies, such as JD.com's supply chain innovations, illustrate AI's transformative impact. The survey concludes by suggesting future research directions and practical implications for stakeholders, advocating for the integration of AI with other emerging technologies to enhance supply chain flexibility and resilience. By leveraging AI, supply chains can achieve greater adaptability and efficiency, ensuring continuity in the face of disruptions.

1 Introduction

1.1 Structure of the Survey

This survey offers a thorough examination of AI applications in supply chains, emphasizing logistics enhancement, digital transformation, and resilience. It begins by highlighting the significance of AI in addressing technological capability asymmetry and risk management. The background and definitions section provides foundational insights into key concepts such as technological capability asymmetry, supply chain resilience, and digital transformation, clarifying their interrelations.

Subsequent sections investigate AI's role in logistics optimization and its contribution to digital supply chain transformation and Industry 4.0 adoption. The discussion includes AI-driven optimization techniques and case studies that demonstrate AI's impact on supply chain processes.

The survey further delves into the challenges and opportunities arising from technological capability asymmetry among supply chain partners, illustrating how AI can bridge these gaps. This integration enhances operational efficiency, resilience, and adaptability, ultimately improving performance and sustainability in a dynamic digital environment [1, 2, 3, 4, 5]. It discusses frameworks and models that leverage AI to address these asymmetries, emphasizing collaboration and trust in overcoming challenges.

Further analysis focuses on how AI bolsters supply chain resilience through strategies for risk management, disruption prediction, and recovery. The interplay between AI and digital transformation in enhancing resilience is examined, alongside collaborative AI approaches.

The penultimate section details AI's role in risk management, covering techniques for risk identification, assessment, and mitigation. It emphasizes strategies for improving decision-making through AI, particularly in predicting disruptions and facilitating recovery efforts.

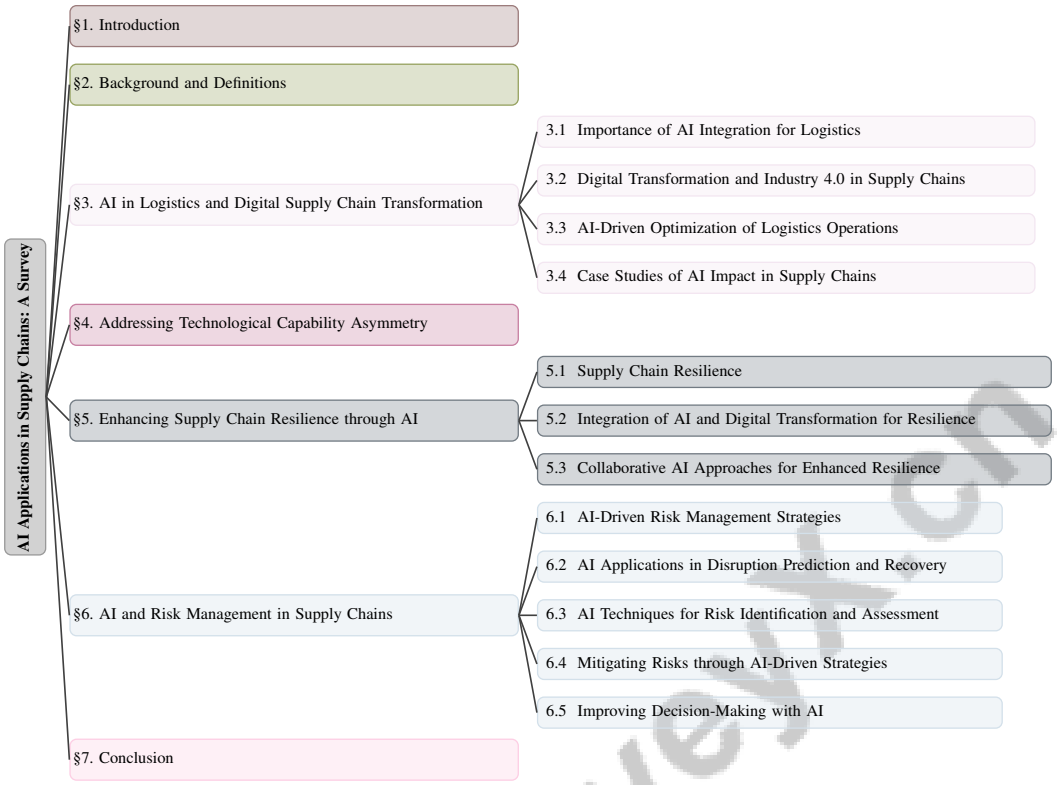


Figure 1: chapter structure

The survey concludes by summarizing key findings and reflecting on AI's transformative potential in supply chains. It outlines future research directions for integrating AI and Big Data Analytics (BDA) in supply chain risk management, focusing on mitigating technological capability asymmetry, enhancing resilience, and improving risk management practices. By establishing a comprehensive framework linking Industry 4.0 technologies with supply chain resilience, the study aims to guide industry stakeholders in leveraging these advanced technologies to anticipate and respond to disruptions, as highlighted by the challenges of the COVID-19 pandemic [6, 7, 8].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Interrelation of Core Concepts

The interconnection between technological capability asymmetry, supply chain resilience, and digital transformation, particularly through AI, presents a complex challenge in modern supply chain management. Technological capability asymmetry, characterized by disparities in technology adoption and utilization among supply chain partners, hampers effective integration and optimization [9]. This issue is exacerbated by the rapid technological advancements and the complexities of integrating innovations like blockchain and IoT into existing frameworks [10]. Additionally, resistance to change from established practices further complicates these challenges.

AI and Industry 4.0 technologies drive digital transformation, aiming to mitigate these asymmetries by enhancing connectivity, data processing, and decision-making across supply chain networks [2]. While AI integration can improve efficiency, resource sharing, and communication, it cannot replace the crucial role of trust in supplier relationships [11]. The Technology-Organization-Environment (TOE) framework outlines the technological, organizational, and environmental factors influencing digital supply chain adoption, emphasizing the contexts shaping transformation efforts [12]. However, the absence of a clear conceptual framework linking Industry 4.0 with supply chain management and the lack of maturity propositions for Supply Chain 4.0 remain significant hurdles [13].

Supply chain resilience, closely linked to these concepts, involves the capacity to withstand, adapt to, and recover from disruptions. AI and big data analytics (BDA) are crucial in enhancing resilience across various phases, including readiness, response, recovery, and adaptability [6]. Integrating emerging ICTs, such as blockchain and AI, is vital for improving supply chain performance and resilience while reducing environmental impacts [3]. Digital transformation further enhances sustainable supply chain performance and resilience by fostering greater integration [14].

To fully leverage AI's transformative potential, addressing technological capability asymmetry and promoting alignment among supply chain partners is essential. This necessitates collaborative strategies that enhance visibility and resilience, ultimately leading to robust, digitally advanced, and equitable supply chains [7].

3 AI in Logistics and Digital Supply Chain Transformation

The integration of artificial intelligence (AI) into logistics is central to the digital transformation of supply chains, fundamentally altering operational practices. Organizations are increasingly recognizing AI's potential to enhance efficiency and adapt to market dynamics, particularly within Industry 4.0, which emphasizes interconnectivity, digitalization, and automation as enablers for Smart Logistics. AI optimizes transportation routes, improves demand forecasting accuracy, and enhances resource management through predictive analytics, making it essential for maintaining competitiveness [15, 6, 16, 17, 5].

As illustrated in Figure 2, the hierarchical structure of AI's integration into logistics and digital supply chain transformation is depicted, highlighting key areas such as operational efficiency, technological integration, AI-driven optimization, and case studies of AI impact. This figure categorizes the primary concepts and their subcategories, demonstrating AI's role in enhancing efficiency, transparency, and resilience in supply chains. This section explores AI's critical role in driving operational excellence and competitive advantage in logistics.

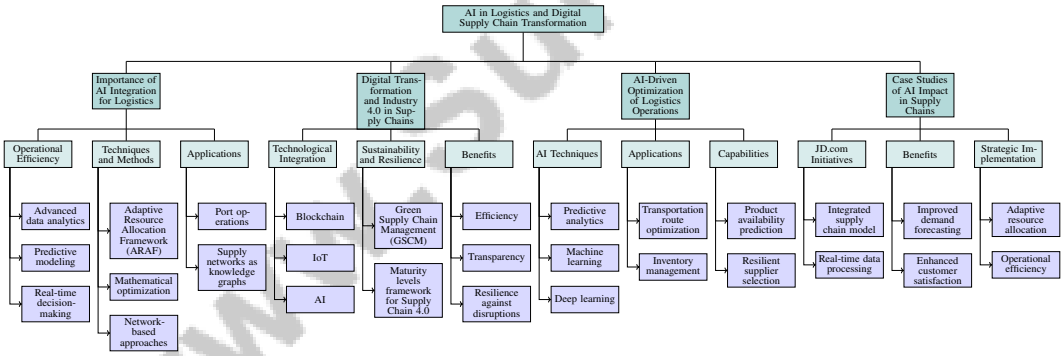


Figure 2: This figure illustrates the hierarchical structure of AI's integration into logistics and digital supply chain transformation, highlighting key areas such as operational efficiency, technological integration, AI-driven optimization, and case studies of AI impact. It categorizes the primary concepts and their subcategories, demonstrating AI's role in enhancing efficiency, transparency, and resilience in supply chains.

3.1 Importance of AI Integration for Logistics

AI integration in logistics is crucial for enhancing operational efficiency and effectiveness. It enables advanced data analytics, predictive modeling, and real-time decision-making, optimizing supply chain operations. AI-driven digital transformation enhances supply chain finance (SCF) solutions, improving cash flow management and minimizing risks [18]. Furthermore, AI strengthens supply chain resilience through improved demand forecasting, transparency, and operational efficiency [19].

As illustrated in Figure 3, the hierarchical structure of AI integration in logistics highlights three primary categories: Operational Efficiency, Supply Chain Resilience, and Digital Transformation. Each category encompasses key AI applications, such as route optimization, predictive analytics,

demand forecasting, and knowledge graph utilization, effectively demonstrating their collective impact on enhancing logistics operations and resilience.

AI optimizes routes and reduces computation times, adapting to complex logistics scenarios to enhance efficiency [17]. Techniques like the Adaptive Resource Allocation Framework (ARAF) demonstrate AI's impact on logistics by improving resource utilization and response times [20]. Predictive analytics also contribute to operational efficiency and cost reduction [5].

AI methods, including mathematical optimization, network-based approaches, agent-based modeling, automated reasoning, and machine learning, offer diverse logistics applications [21]. These methods enhance efficiency, visibility, and safety, especially in port operations, where digital transformation has made a significant impact [22]. Modeling supply networks as knowledge graphs improves transparency by linking various data sources, extending visibility to tier-3 suppliers [23].

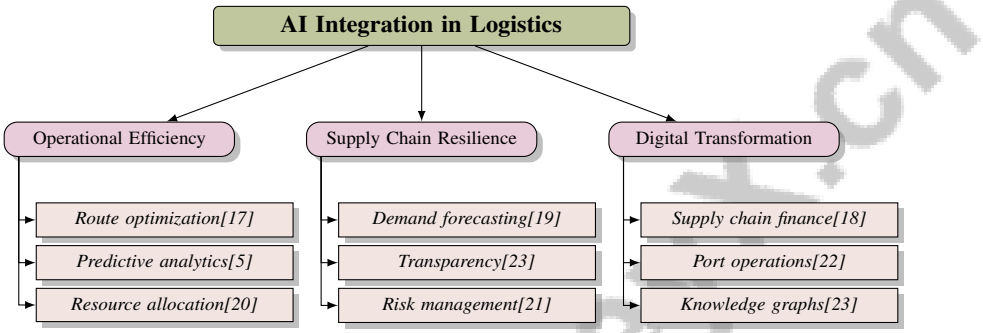


Figure 3: This figure shows the hierarchical structure of AI integration in logistics, highlighting three primary categories: Operational Efficiency, Supply Chain Resilience, and Digital Transformation. Each category includes key AI applications such as route optimization, predictive analytics, demand forecasting, and knowledge graph utilization, illustrating their impact on enhancing logistics operations and resilience.

3.2 Digital Transformation and Industry 4.0 in Supply Chains

AI's integration within digital transformation and Industry 4.0 frameworks is critical for enhancing supply chain efficiency, transparency, and resilience. Industry 4.0, characterized by digital technologies like blockchain, IoT, and AI, promises improved decision-making and information sharing. However, companies often hesitate to adopt these technologies due to competitive concerns [9]. The adoption of digital technologies is essential for supply chain optimization, significantly enhancing operational efficiency and reducing costs.

AI enhances data transparency and traceability, particularly in complex supply chains like the food industry. The integration of AI with Blockchain Technology (BCT) creates a unified framework that improves data transparency and traceability, as evidenced in the fish industry [24]. This integration is vital for advancing sustainable supply chain practices, as explored in agriculture and Industry 4.0 contexts [25].

A configurational approach to digital transformation, incorporating dimensions of Green Supply Chain Management (GSCM), has not been comprehensively studied [26]. This approach emphasizes AI's potential to drive sustainable practices within supply chains. Additionally, a two-dimensional model of digital technology adoption, based on technological intelligence and supply chain cooperation, highlights AI's strategic importance in fostering collaboration and innovation [27].

The introduction of a maturity levels framework for Supply Chain 4.0 addresses a critical gap in the literature, offering a structured method to evaluate the adoption and integration of Industry 4.0 technologies [13]. This framework categorizes these technologies and their relationships with supply chain resilience antecedents and phases, providing a comprehensive view of how digital transformation enhances resilience [7].

Current research emphasizes the benefits of integrating digital technologies in supply chains, revealing enhancements in efficiency, transparency, and resilience against disruptions [10]. As AI continues to

drive digital transformation, its role in advancing Industry 4.0 adoption will be pivotal for achieving sustainable and resilient supply chains.

3.3 AI-Driven Optimization of Logistics Operations

AI-driven optimization in logistics operations leverages advanced technologies to enhance supply chain performance and efficiency. The application of AI techniques, such as predictive analytics and machine learning, is crucial for optimizing logistics processes, thereby improving decision-making and operational effectiveness. The AlaR method exemplifies AI's role in optimizing logistics and inventory management within the automotive supply chain, leading to increased efficiency and cost reduction [5].

AI large models based on deep learning and reinforcement learning have proven instrumental in analyzing and optimizing transportation routes using real-world data, significantly boosting adaptability and responsiveness in logistics operations [17]. The integration of supervised machine learning with simulation further supports data-driven decision-making models, essential for resilient supplier selection and supply chain optimization [28].

AI's predictive capabilities regarding product availability dates enhance supply chain resilience by enabling better management of disruptions and minimizing logistics-related risks [29]. Recognizing Smart Technologies (STs) as transformative for logistics and transport underscores ongoing evolution and optimization challenges, suggesting future research directions to improve logistics operations [30].

3.4 Case Studies of AI Impact in Supply Chains

The impact of AI on supply chain processes is exemplified by JD.com's strategic initiatives, demonstrating superior resilience through an integrated supply chain model leveraging AI and digital technologies. This proactive approach has enabled JD.com to outperform competitors in supply chain resilience and efficiency [31]. AI-driven predictive analytics and real-time data processing have improved demand forecasting, inventory management, and logistics optimization, enhancing overall performance.

JD.com's success illustrates AI's transformative potential in supply chain management, showcasing how digital integration can lead to significant operational improvements. By analyzing vast data sets to predict consumer demand, JD.com optimizes logistics operations, reduces costs, and enhances customer satisfaction. This case study highlights AI's critical role in fostering a resilient and adaptable supply chain, particularly in light of recent disruptions like the COVID-19 pandemic. It demonstrates that integrating AI and big data analytics into supply chain strategies enhances transparency, risk management, and agile procurement, providing substantial competitive advantages. Research indicates that leveraging AI improves short-term performance while building long-term resilience, making it essential for organizations navigating modern supply chain complexities [4, 6, 19].

Furthermore, JD.com's proactive use of digital technologies has enabled it to maintain supply chain continuity and adaptability amid disruptions. The strategic implementation of AI for real-time decision-making and adaptive resource allocation has been critical in enhancing operational efficiency and mitigating adverse effects from external disruptions. Empirical research underscores AI's role in improving supply chain resilience and performance within dynamic market conditions. By integrating AI-driven analytics and predictive modeling, JD.com has optimized demand forecasting and operational agility while establishing a framework for sustained resilience, effectively positioning itself against future uncertainties [6, 19, 16, 8, 4]. This example underscores AI's essential role in developing robust supply chains capable of withstanding and recovering from disruptions, offering valuable insights for firms seeking to enhance resilience through digital transformation.

4 Addressing Technological Capability Asymmetry

In the context of addressing technological capability asymmetry, it is imperative to explore the multifaceted opportunities that arise for bridging capability gaps among supply chain partners. This subsection delves into the various avenues through which artificial intelligence (AI) can facilitate

enhanced collaboration, operational efficiency, and resilience within supply chains. By examining the transformative potential of AI technologies, we can better understand how they contribute to a more integrated and adaptive supply chain ecosystem, ultimately leading to improved performance and strategic alignment among partners.

4.1 Opportunities for Bridging Capability Gaps

The integration of artificial intelligence (AI) into supply chain management offers substantial opportunities for bridging capability gaps among partners, thereby enhancing overall efficiency and resilience. AI technologies facilitate improved forecasting accuracy and operational efficiency by enabling a collaborative interface between AI systems and human expertise, allowing firms to respond more effectively to disruptions [32]. The dynamic nature of AI-driven frameworks, such as the Adaptive Resource Allocation Framework (ARAF), enhances resource allocation efficiency and responsiveness, thus addressing capability gaps and fostering collaboration among supply chain partners [30].

One of the primary advantages of AI is its ability to provide real-time insights and predictive capabilities, which significantly enhance decision-making processes in supply chain management. By leveraging AI, supply chains can achieve greater visibility and flexibility, crucial for effective risk management and bridging technological asymmetries [33]. This increased visibility allows for better alignment of strategies and resources across the supply chain, reducing the tendency for companies to adopt isolated security measures that do not consider the entire supply chain [11].

AI also plays a critical role in enhancing data transparency and fostering cooperation among supply chain partners. This transparency is essential for reducing biases in decision-making and improving responsiveness to disruptions through data-driven approaches [34]. Moreover, the adoption of digital supply chains, driven by perceived benefits, cost-effectiveness, and security, is more likely in industries that recognize the strategic advantages of AI integration [35].

Despite the challenges posed by the unpredictability of global disruptions and the limitations of existing resilience strategies, AI offers a flexible and adaptive framework for resilience planning [13]. By bridging capability gaps, AI not only enhances operational efficiency but also strengthens the strategic alignment and collaboration necessary for resilient and adaptive supply chains.

4.2 Frameworks and Models Addressing Asymmetry

The development of frameworks and models that leverage artificial intelligence (AI) is critical in addressing technological capability asymmetry within supply chains. These frameworks aim to enhance collaboration, transparency, and operational efficiency by integrating AI technologies into existing supply chain processes. A notable contribution in this area is the introduction of a framework that categorizes research on blockchain and AI in supply chains, focusing on their potential to boost transparency, traceability, and efficiency while aligning with sustainability objectives [3].

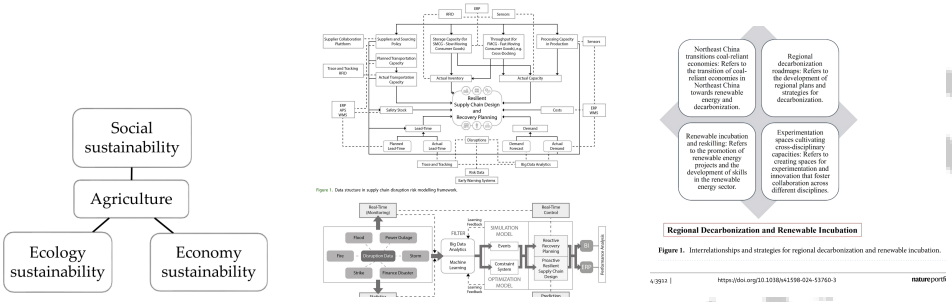
One effective framework is the SCRE Capability-Performance Metrics Framework (SCPM), which categorizes supply chain resilience into readiness, response, and recovery dimensions. This framework provides a structured approach to understanding and evaluating performance across different phases of supply chain operations, emphasizing the importance of preemptive readiness, effective response to disruptions, and efficient recovery [36]. The SCPM framework is instrumental in bridging capability gaps by providing clear metrics for performance evaluation.

The Dynamic Resilience Planning Framework (DRPF) further addresses these asymmetries by focusing on data collection, feature selection, and algorithm choice tailored to specific supply chain goals. This framework utilizes AI-driven strategies to optimize decision-making processes, thereby enhancing adaptability and resilience among supply chain partners [8]. The DRPF's emphasis on data-driven decision-making is crucial for addressing technological disparities and enhancing supply chain performance.

Additionally, the integration of system dynamics and discrete event simulation offers a comprehensive model for addressing technological capability asymmetry. This approach leverages AI to enable dynamic and flexible resource allocation and decision-making, fostering greater alignment and cooperation among supply chain partners [32]. Such integration is vital for creating resilient supply chains capable of adapting to changing conditions.

Contractual and relational governance mechanisms play a pivotal role in managing information asymmetry within supply chains. When combined with AI-driven frameworks, these mechanisms enhance information sharing and strategic alignment, reducing the impact of capability disparities [37]. The study further underscores the need for firms to invest in technologies that enhance visibility and communication without undermining relational trust [11].

Despite these advancements, unanswered questions remain regarding the specific application of frameworks like ISO 31000 in diverse industrial contexts and their effectiveness in addressing technological capability asymmetry [38]. Continued research and development of AI-driven frameworks are essential for overcoming these challenges and building resilient, efficient supply chains.



(a) Agriculture and its sustainability aspects[25]

(b) Data Structure in Supply Chain Disruption Risk Modelling Framework[39]

(c) Regional Decarbonization and Renewable Incubation[3]

Figure 4: Examples of Frameworks and Models Addressing Asymmetry

As shown in Figure 4, The example of "Addressing Technological Capability Asymmetry; Frameworks and Models Addressing Asymmetry" is illustrated through three distinct yet interconnected visual representations, each focusing on a different domain of technological and sustainability challenges. The first figure, "Agriculture and its sustainability aspects," presents a flowchart that captures the intricate balance between social, ecological, and economic sustainability within the realm of agriculture. This diagram underscores the pivotal role agriculture plays in sustaining these three critical dimensions. The second figure, "Data Structure in Supply Chain Disruption Risk Modelling Framework," offers a detailed flowchart that maps out the components and interactions vital for designing resilient supply chains and recovery planning, highlighting the importance of robust data structures in mitigating disruption risks. Lastly, the "Regional Decarbonization and Renewable Incubation" figure, derived from a Nature Portfolio publication, explores strategies for transitioning coal-reliant economies in Northeast China towards renewable energy and decarbonization. Each of these frameworks exemplifies unique approaches to addressing the asymmetries in technological capabilities, emphasizing the need for tailored strategies across different sectors to achieve sustainable development and resilience. [**?**]hrustek2020sustainability,ivanov2021digital,hong2024digital)

4.3 Role of Collaboration and Trust

The role of collaboration and trust in overcoming technological capability asymmetry within supply chains is of paramount importance. Collaborative efforts among supply chain partners are essential for addressing disparities in technological capabilities, as they facilitate the sharing of resources, knowledge, and best practices. Trust serves as the foundational element that underpins successful collaboration, enabling partners to engage openly and transparently in joint initiatives aimed at bridging capability gaps [11].

Trust reduces the perceived risks associated with sharing sensitive information and adopting new technologies, which is crucial for overcoming resistance to change and fostering a culture of innovation. The integration of AI and digital technologies can enhance trust by providing transparent, data-driven insights that improve decision-making and accountability across the supply chain [34]. This transparency is vital for mitigating information asymmetry and ensuring that all partners have access to accurate and timely data, thereby facilitating more effective collaboration.

Moreover, the development of trust-based relationships is critical for the successful implementation of AI-driven frameworks that address technological capability asymmetry. Trust encourages partners

AI-generated, for reference only.

to invest in long-term strategic alliances, which are necessary for achieving sustainable improvements in supply chain performance [37]. Collaborative governance mechanisms, such as joint ventures and strategic partnerships, further strengthen trust by aligning the interests of all parties involved and promoting a shared commitment to overcoming capability disparities.

In addition to fostering trust, collaboration enables supply chain partners to leverage complementary strengths, thereby enhancing overall resilience and adaptability. Collaborative approaches that integrate AI and other digital technologies can lead to more efficient resource allocation, improved risk management, and enhanced supply chain visibility [32]. These benefits are particularly important in the context of global supply chains, where diverse partners must work together to navigate complex and dynamic environments.

The significance of collaboration and trust in addressing technological capability asymmetry is crucial, as effective inter-organizational governance mechanisms enable partners to process information and make informed decisions, particularly in the context of digital transformation, where reliance on shared information is essential for enhancing supply chain resilience and overall performance. [18, 37, 11]. As supply chains continue to evolve in response to technological advancements and market demands, fostering trust-based, collaborative relationships will be essential for achieving sustainable, resilient, and equitable supply chain networks.

5 Enhancing Supply Chain Resilience through AI

5.1 Supply Chain Resilience

Supply chain resilience is the capacity of supply chains to anticipate, adapt, respond, recover, and learn from disruptions while maintaining core functions [35]. The COVID-19 pandemic exposed vulnerabilities in traditional supply chain models, emphasizing the need for resilience alongside profitability [34, 40]. Resilience enables rapid adaptation to market changes, as evidenced by the flexibility and collaboration of leading firms during the pandemic [31]. It involves more than shock prevention; it encompasses swift recovery and operational continuity, as seen in sectors like automotive and airlines [4]. Incorporating AI into supply chains enhances resilience through predictive analytics, optimizing logistics and inventory management [5].

AI's advanced predictive capabilities are crucial for effective risk management [33]. AI frameworks provide structured risk management approaches, enabling the anticipation of disruptions and proactive countermeasures [4]. Trust is fundamental for joint problem-solving, fostering resilience through informed decision-making and agility [11, 6]. Traditional risk management often falls short, prompting a shift towards proactive AI-driven solutions [38, 41]. Leveraging AI ensures preparedness and continuity amid global changes [9].

5.2 Integration of AI and Digital Transformation for Resilience

Integrating AI with digital transformation is essential for enhancing supply chain resilience, enabling anticipation, adaptation, and response to disruptions. This integration supports proactive and reactive strategies, fostering innovation and recovery [35]. Digital transformation enhances supply chain processes through real-time data analysis, improving decision-making and responsiveness [42]. AI frameworks offer predictive capabilities, facilitating risk management and disruption mitigation [34]. For instance, AI optimizes logistics and inventory via predictive analytics [40].

Strategically aligning AI with digital transformation is vital for resilience. Integrating Industry 4.0 technologies improves resilience by enhancing anticipation and response to disruptions [7]. Frameworks emphasizing collaboration, information sharing, and agility, such as JD.com's integrated supply chain, exemplify this integration [31]. Building resilience impacts firm performance and customer value [43]. AI and digital transformation enable proactive risk management, ensuring preparedness and continuity in a dynamic global landscape [38].

5.3 Collaborative AI Approaches for Enhanced Resilience

Collaborative AI strategies are crucial for enhancing supply chain resilience, fostering innovation, empowerment, and effective risk management. These strategies emphasize stakeholder collaboration, essential for building resilient supply chains [44]. Integrating AI with collaborative frameworks

allows real-time insights and data-driven decision-making, enhancing flexibility and adaptability [45].

Larger firms often excel in risk management due to their resources, underscoring the need for smaller firms to adopt innovative, collaborative AI strategies to enhance resilience [46]. A dual approach, leveraging existing IT resources while exploring new technologies, is essential for balancing short-term efficiency with long-term adaptability [43]. Collaborative AI involves integrating smart technologies to address logistics uncertainties, including last-mile delivery. Future research should develop robust optimization techniques incorporating these technologies to enhance resilience [30]. A practical framework guiding firms in resilience enhancement during disruptions is crucial for effective and sustainable collaborative AI implementation [34].

6 AI and Risk Management in Supply Chains

6.1 AI-Driven Risk Management Strategies

Method Name	Technological Integration	Process Stages	Innovative Techniques
DRPF[8]	AI Techniques	Method Steps	Advanced Machine Learning
IHSF[32]	System Dynamics	Method Steps	Multiple Simulation Techniques
QMC[47]	-	Risk Identification, Assessment	Quantum Monte Carlo
PSCRM[41]	-	Risk Identification, Assessment	Linear Programming, Ai-driven

Table 1: Comparison of AI-Driven Risk Management Methods in Supply Chain Resilience, detailing Technological Integration, Process Stages, and Innovative Techniques.

AI-driven strategies are pivotal in enhancing supply chain resilience by leveraging advanced technologies to anticipate, assess, and mitigate risks. The Data-Driven Risk Prediction Framework (DRPF) exemplifies this integration, combining AI techniques with traditional supply chain practices for predictive risk analysis while ensuring interpretability [8]. This framework underscores the role of predictive analytics in identifying disruptions and implementing proactive measures.

A hybrid simulation framework effectively models supply chain resilience under non-stationary pandemic demand, showcasing dynamic AI-driven frameworks for complex challenges [32]. Research categorizes existing studies into four stages: risk identification, assessment, treatment, and monitoring, providing a comprehensive overview of AI's role in supply chain risk management [33].

Table 1 presents a comparative analysis of various AI-driven risk management methods, highlighting their technological integration, process stages, and innovative techniques, thereby providing insights into their applications in enhancing supply chain resilience. AI enhances supply chain resilience (SCRes) and performance (SCP) through improved information processing and decision-making capabilities [4]. Adoption of AI, adaptive capabilities, and collaboration can significantly boost supply chain performance [40]. Investment in IT exploration is crucial for building resilient supply chains, highlighting AI's strategic importance in modern management [43].

The transformative potential of AI in modernizing port operations illustrates its efficiency and risk reduction capabilities [22]. Despite this, establishing a unified supply chain risk management methodology remains challenging due to varied steps proposed by researchers [38].

Quantum Monte Carlo (QMC) methods represent a frontier in AI-driven risk management, leveraging quantum algorithms for efficient processing of complex probabilistic models, optimizing inventory decisions [47]. This innovation opens new avenues for enhancing supply chain resilience.

A proactive risk management approach integrating risk profiles into procurement strategies significantly enhances resilience and reduces disruption costs [41]. Leveraging AI technologies enables better anticipation and mitigation of risks, ensuring continuity amid disruptions.

6.2 AI Applications in Disruption Prediction and Recovery

AI applications in disruption prediction and recovery are essential for enhancing supply chain resilience and efficiency. Advanced predictive analytics and machine learning algorithms enable AI to forecast disruptions and optimize recovery strategies, minimizing operational impacts. The method proposed by [5] focuses on predicting product movement and optimizing shipment schedules, significantly improving efficiency and reducing costs.

The Integrated Hybrid Simulation Framework (IHSF) developed by [32] demonstrates AI's application in predicting demand for critical resources, such as oxygen concentrators during pandemics. This framework supports disruption prediction and recovery efforts, allowing supply chains to swiftly adapt to changing demand patterns and maintain operational continuity.

A structured approach to risk management, based on the ISO 31000 framework, organizes AI-driven disruption prediction and recovery strategies into stages such as risk identification, evaluation, treatment, and monitoring [38]. AI technologies enhance each stage with real-time data insights and predictive capabilities, enabling proactive responses to potential threats.

6.3 AI Techniques for Risk Identification and Assessment

Effective supply chain risk management (SCRM) hinges on risk identification and assessment, where AI techniques provide advanced analytical capabilities to improve prediction accuracy and efficiency. The irregular nature of disruptions complicates risk identification, yet AI technologies, particularly machine learning algorithms, can analyze large datasets to discern patterns and predict risks such as delivery delays, threatening operations and profitability [8].

Integrating AI into risk assessment involves using knowledge graphs to enhance transparency and improve risk prediction by organizing and visualizing supply chain data [23]. This method fosters a comprehensive understanding of the supply chain network, facilitating more accurate risk assessments and informed decision-making. However, research gaps persist regarding the long-term implications of AI integration and the evolving roles of human workers [16].

The adoption of Smart Technologies (STs) introduces complexities in modeling and optimization, requiring more sophisticated AI models that account for the interconnected nature of modern supply chains [30]. The lack of a unified definition of SCRM complicates these efforts, underscoring the need for a thorough understanding of its stages and theoretical foundations [33].

6.4 Mitigating Risks through AI-Driven Strategies

AI-driven strategies are crucial for mitigating risks in supply chains by enhancing decision-making and fostering resilience. The integration of AI technologies enables the development of sophisticated models for effective risk management. For instance, supervised machine learning models facilitate data-driven decision-making, vital for implementing effective risk mitigation strategies in supply chain management [28].

The synergy between AI and Blockchain Technology (BCT) enhances collaborative risk management efforts by combining AI's analytical power with BCT's data integrity and security [24]. AI's capacity to analyze large datasets provides actionable insights for identifying risks and implementing preemptive measures.

Moreover, the concept of IT ambidexterity, balancing exploitative and explorative IT use, is essential for improving supply chain resilience. This dual approach reconciles leveraging existing IT resources while exploring new technological opportunities [43]. By adopting this strategy, firms can better anticipate and respond to disruptions, ensuring operational continuity.

Effective control of digital transformation supply chain resilience (DTSCR) is critical for risk mitigation. Focusing on risk management during digital transformation enhances resilience, equipping enterprises to navigate digital integration challenges [48]. This proactive approach emphasizes aligning digital transformation initiatives with strategic risk mitigation efforts.

A proactive risk management strategy that actively manages supplier risks offers substantial benefits in minimizing disruptions and reducing costs over time [41]. By anticipating supplier-related risks and implementing measures to address them, supply chains enhance continuity and operational efficiency amid unforeseen challenges.

Despite these advancements, challenges remain, including limited theoretical applications in existing research and the need for a holistic understanding of SCRM across various contexts [33]. Continued research and development of AI-driven strategies are essential for overcoming these challenges and building resilient, efficient supply chains capable of effective risk mitigation.

6.5 Improving Decision-Making with AI

Integrating artificial intelligence (AI) into supply chain risk management significantly enhances decision-making processes through advanced data analytics and information control principles. AI's capacity to process vast datasets and deliver actionable insights is crucial for improving decision-making efficiency and accuracy in risk management. A theoretical framework combining cybernetics and information control principles provides a robust foundation for enhancing decision-making capabilities within supply chains [39].

AI-driven decision-making is characterized by a data-driven approach that optimizes supply chain performance through informed and timely decisions. Research highlights data analytics' critical role in optimizing operations, illustrating how AI transforms decision-making processes by offering real-time insights and predictive capabilities [4]. This transformation is essential for maintaining competitiveness and ensuring adaptability to changing conditions.

Furthermore, AI contributes to decision-making by enhancing supply chain resilience, vital for sustaining competitive advantage in dynamic markets. AI-driven analytics empower practitioners to develop effective risk management strategies, ensuring supply chains remain resilient against disruptions [40]. By facilitating proactive decision-making, AI helps supply chains anticipate risks and implement mitigation measures, thereby enhancing overall resilience and performance.

7 Conclusion

The exploration of artificial intelligence (AI) within supply chain management underscores its transformative capacity to address key challenges such as technological capability asymmetry, resilience enhancement, and risk management. By enabling sophisticated data analytics, predictive modeling, and real-time decision-making, AI facilitates the optimization of operations and the refinement of supply chain finance mechanisms. Notably, AI-driven frameworks, including the Adaptive Resource Allocation Framework, have shown significant advancements in resource management and operational effectiveness. Furthermore, the integration of AI with Blockchain Technology enhances data transparency and traceability, which are crucial for sustainable supply chain practices.

The findings emphasize the importance of contractual control and relational governance in improving decision-making processes across supply chains. The proposed Digital Supply Chain model, which integrates traditional management constructs with Industry 4.0 elements, supports enhanced performance and adaptability. Future research should focus on empirical validation of these frameworks, exploring the linkages between supply chain resilience capabilities and performance metrics, and assessing the impact of emerging disruptions.

Further research is needed to explore the synergy between AI and other emerging technologies, such as 5G, to improve supply chain flexibility and develop standardized frameworks for AI adoption. Overcoming barriers to technology adoption and evaluating the effects of digital transformations across different geographical regions are crucial for boosting supply chain efficiency and resilience. The emergence of smart supply chains leveraging AI and machine learning for enhanced traceability and compliance represents a promising research direction.

For industry stakeholders, the practical implications stress the importance of fostering collaboration across supply chains, considering the human element in risk management, and developing integrated strategies that go beyond individual organizations. Longitudinal studies should assess the long-term impact of risk management capabilities on competitive advantage and facilitate cross-country comparisons to enhance generalizability. By leveraging AI and digital transformation, supply chains can achieve improved resilience, adaptability, and efficiency, thereby positioning themselves to effectively navigate future disruptions and maintain continuity in an increasingly dynamic global environment.

The proposed frameworks provide a robust foundation for the understanding and implementation of Supply Chain 4.0, addressing significant gaps in the existing literature.

References

[1] Mohsen Attaran. Digital technology enablers and their implications for supply chain management. In *Supply Chain Forum: An International Journal*, volume 21, pages 158–172. Taylor & Francis, 2020.

[2] Guoqing Zhang, Yiqin Yang, and Guoqing Yang. Smart supply chain management in industry 4.0: the review, research agenda and strategies in north america. *Annals of operations research*, 322(2):1075–1117, 2023.

[3] Zexin Hong and Kun Xiao. Digital economy structuring for sustainable development: the role of blockchain and artificial intelligence in improving supply chain and reducing negative environmental impacts. *Scientific Reports*, 14(1):3912, 2024.

[4] Amine Belhadi, Venkatesh Mani, Sachin S Kamble, Syed Abdul Rehman Khan, and Surabhi Verma. Artificial intelligence-driven innovation for enhancing supply chain resilience and performance under the effect of supply chain dynamism: an empirical investigation. *Annals of Operations Research*, 333(2):627–652, 2024.

[5] Vishwanadham Mandala and Dilip Kumar Vaka. Revolutionizing asynchronousshipments: Integrating ai predictiveanalytics in automotive supplychains. *International Journal of Artificial Intelligence & Machine Learning (IJAIML)*, 1(01):47–59, 2022.

[6] Efpraxia D Zamani, Conn Smyth, Samrat Gupta, and Denis Dennehy. Artificial intelligence and big data analytics for supply chain resilience: a systematic literature review. *Annals of Operations Research*, 327(2):605–632, 2023.

[7] Alexander Spieske and Hendrik Birkel. Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the covid-19 pandemic. *Computers & Industrial Engineering*, 158:107452, 2021.

[8] George Baryannis, Samir Dani, and Grigoris Antoniou. Predicting supply chain risks using machine learning: The trade-off between performance and interpretability. *Future Generation Computer Systems*, 101:993–1004, 2019.

[9] Raphael Preindl, Konstantinos Nikolopoulos, and Konstantia Litsiou. Transformation strategies for the supply chain: The impact of industry 4.0 and digital transformation. In *Supply Chain Forum: An International Journal*, volume 21, pages 26–34. Taylor & Francis, 2020.

[10] Syed Baber Ali. Industrial revolution 4.0 and supply chain digitization: Future of supply chain management. *South Asian Journal of Social Review*, 1(1):21–41, 2022.

[11] Murtaza Faruquee, Antony Paulraj, and Chandra Ade Irawan. Strategic supplier relationships and supply chain resilience: is digital transformation that precludes trust beneficial? *International Journal of Operations & Production Management*, 41(7):1192–1219, 2021.

[12] Nuraan Daniels and Osden Jokonya. Factors affecting digital transformation in the retail supply chain. In *International Conference on Multidisciplinary Research*, volume 2020, pages 117–133, 2020.

[13] Guilherme F Frederico, Jose Arturo Garza-Reyes, Anthony Anosike, and Vikas Kumar. Supply chain 4.0: concepts, maturity and research agenda. *Supply Chain Management: An International Journal*, 25(2):262–282, 2019.

[14] Imadeddine Oubrahim, Naoufal Sefiani, and Ari Happonen. The influence of digital transformation and supply chain integration on overall sustainable supply chain performance: An empirical analysis from manufacturing companies in morocco. *Energies*, 16(2):1004, 2023.

[15] Manuel Woschank, Erwin Rauch, and Helmut Zsifkovits. A review of further directions for artificial intelligence, machine learning, and deep learning in smart logistics. *Sustainability*, 12(9):3760, 2020.

[16] KarthikSai Chenna. Optimizing decision-making in supply chains: A framework for ai and human collaboration using sap technologies. *International Journal of Research in Computer Applications and Information Technology (IJRCAIT)*, 7(2):824–835, 2024.

[17] Gang Ping, Mingwei Zhu, Zhipeng Ling, and Kaiyi Niu. Research on optimizing logistics transportation routes using ai large models. *Spectrum of Research*, 4(1), 2024.

[18] Lujie Chen, Antonella Moretto, Fu Jia, Federico Caniato, and Yu Xiong. The role of digital transformation to empower supply chain finance: current research status and future research directions (guest editorial). *International Journal of Operations & Production Management*, 41(4):277–288, 2021.

[19] Sachin Modgil, Rohit Kumar Singh, and Claire Hannibal. Artificial intelligence for supply chain resilience: learning from covid-19. *The International Journal of Logistics Management*, 33(4):1246–1268, 2022.

[20] Mahmoud Ashraf, Amr Eltawil, and Islam Ali. Disruption detection for a cognitive digital supply chain twin using hybrid deep learning, 2023.

[21] George Baryannis, Sahar Validi, Samir Dani, and Grigoris Antoniou. Supply chain risk management and artificial intelligence: state of the art and future research directions. *International journal of production research*, 57(7):2179–2202, 2019.

[22] Leonard Heilig, Silvia Schwarze, and Stefan Voß. An analysis of digital transformation in the history and future of modern ports. 2017.

[23] Yushan Liu, Bailan He, Marcel Hildebrandt, Maximilian Buchner, Daniela Inzko, Roger Wernert, Emanuel Weigel, Dagmar Beyer, Martin Berbalk, and Volker Tresp. A knowledge graph perspective on supply chain resilience, 2023.

[24] Naoum Tsolakis, Roman Schumacher, Manoj Dora, and Mukesh Kumar. Artificial intelligence and blockchain implementation in supply chains: a pathway to sustainability and data monetisation? *Annals of Operations Research*, 327(1):157–210, 2023.

[25] Larisa Hrustek. Sustainability driven by agriculture through digital transformation. *Sustainability*, 12(20):8596, 2020.

[26] Laura V Lerman, Guilherme Brittes Benitez, Julian M Müller, Paulo Renato de Sousa, and Alejandro Germán Frank. Smart green supply chain management: A configurational approach to enhance green performance through digital transformation. *Supply Chain Management: An International Journal*, 27(7):147–176, 2022.

[27] Miying Yang, Mingtao Fu, and Zihan Zhang. The adoption of digital technologies in supply chains: Drivers, process and impact. *Technological Forecasting and Social Change*, 169:120795, 2021.

[28] Ian M Cavalcante, Enzo M Frazzon, Fernando A Forcellini, and Dmitry Ivanov. A supervised machine learning approach to data-driven simulation of resilient supplier selection in digital manufacturing. *International Journal of Information Management*, 49:86–97, 2019.

[29] Mustafa Can Camur, Sandipp Krishnan Ravi, and Shadi Saleh. Enhancing supply chain resilience: A machine learning approach for predicting product availability dates under disruption, 2023.

[30] Sai-Ho Chung. Applications of smart technologies in logistics and transport: A review. *Transportation Research Part E: Logistics and Transportation Review*, 153:102455, 2021.

[31] Zuojun Max Shen and Yiqi Sun. Strengthening supply chain resilience during covid-19: A case study of jd. com. *Journal of Operations Management*, 69(3):359–383, 2023.

[32] Mustafa Can Camur, Chin-Yuan Tseng, Aristotelis E. Thanos, Chelsea C. White, Walter Yund, and Eleftherios Iakovou. An integrated system dynamics and discrete event supply chain simulation framework for supply chain resilience with non-stationary pandemic demand, 2023.

[33] Yiyi Fan and Mark Stevenson. A review of supply chain risk management: definition, theory, and research agenda. *International journal of physical distribution & logistics management*, 48(3):205–230, 2018.

[34] Iwan Vanany, Mohd Helmi Ali, Kim Hua Tan, Ajay Kumar, and Nurhadi Siswanto. A supply chain resilience capability framework and process for mitigating the covid-19 pandemic disruption. *IEEE Transactions on Engineering Management*, 2021.

[35] Abubakar Ali, Amr Mahfouz, and Amr Arisha. Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. *Supply chain management: an international journal*, 22(1):16–39, 2017.

[36] Yu Han, Woon Kian Chong, and Dong Li. A systematic literature review of the capabilities and performance metrics of supply chain resilience. *International Journal of Production Research*, 58(15):4541–4566, 2020.

[37] Tom AE Aben, Wendy van der Valk, Jens K Roehrich, and Kostas Selviaridis. Managing information asymmetry in public–private relationships undergoing a digital transformation: the role of contractual and relational governance. *International Journal of Operations & Production Management*, 41(7):1145–1191, 2021.

[38] Ualison Rebula De Oliveira, Fernando Augusto Silva Marins, Henrique Martins Rocha, and Valério Antonio Pamplona Salomon. The iso 31000 standard in supply chain risk management. *Journal of Cleaner Production*, 151:616–633, 2017.

[39] Dmitry Ivanov and Alexandre Dolgui. A digital supply chain twin for managing the disruption risks and resilience in the era of industry 4.0. *Production Planning & Control*, 32(9):775–788, 2021.

[40] Aamir Hashmi. Factors affecting the supply chain resilience and supply chain performance. *South Asian Journal of Operations and Logistics*, 1(2):65–85, 2022.

[41] Oguzhan Kırılmaz and Serpil Erol. A proactive approach to supply chain risk management: Shifting orders among suppliers to mitigate the supply side risks. *Journal of Purchasing and Supply Management*, 23(1):54–65, 2017.

[42] Bernardine Chidozie, Ana Ramos, José Ferreira, and Luis Pinto Ferreira. The importance of digital transformation (5.0) in supply chain optimization: an empirical study. *Production Engineering Archives*, 30, 2024.

[43] Minhao Gu, Lu Yang, and Baofeng Huo. The impact of information technology usage on supply chain resilience and performance: An ambidexterous view. *International journal of production economics*, 232:107956, 2021.

[44] Amine Belhadi, Sachin Kamble, Charbel Jose Chiappetta Jabbour, Angappa Gunasekaran, Nelson Oly Ndubisi, and Mani Venkatesh. Manufacturing and service supply chain resilience to the covid-19 outbreak: Lessons learned from the automobile and airline industries. *Technological forecasting and social change*, 163:120447, 2021.

[45] Alireza Aliahmadi, Hamed Nozari, Javid Ghahremani-Nahr, and Agnieszka Szmelter-Jarosz. Evaluation of key impression of resilient supply chain based on artificial intelligence of things (aiot), 2022.

[46] Dilek Ozdemir, Mahak Sharma, Amandeep Dhir, and Tugrul Daim. Supply chain resilience during the covid-19 pandemic. *Technology in society*, 68:101847, 2022.

[47] Monit Sharma and Hoong Chuin Lau. Quantum monte carlo methods for newsvendor problem with multiple unreliable suppliers, 2024.

[48] Yang Gao, Yubing Leng, and Biaoan Shan. Control supply chain risks in digital transformation: A new way to improve supply chain resilience. *Journal of Organizational and End User Computing (JOEUC)*, 34(7):1–18, 2022.

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