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Global supply chain disruptions and its impact on crisis management in multinational companies: Strategies to mitigate risk and increase resilience

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Abstract

In an ever-changing world, supply chains are constantly facing new challenges due to pandemics, geopolitical tensions, and climate change, which poses significant challenges for crisis management in multinational companies. This master’s thesis examines how multinational companies can strengthen their resilience through the use of sustainable practices in combination with new technologies and thus minimize the risk of their global supply chain. Based on this, the theoretical foundation of supply chain resilience, crisis, and risk management as well as the role of innovation and sustainability are analyzed using the guidelines of an integrative literature review according to Snyder (2019). The aim was to use the thematic analysis to identify key strategies such as digital twins, AI-supported early warning systems and sustainable procurement processes and their interplay in terms of strengthening resilience in order to bring them together in a holistic model. The holistic model developed combines the triple bottom line approach by Elkington (1997) and innovative technologies with the aim of crisis prevention and management of supply chain disruptions. The results show that the combination of various innovative technologies in a digital ecosystem can lead to a structured, cross-industry solution approach for future-oriented crisis management. AI-supported risk analyses, blockchain-based transparency solutions and IoT-supported real-time monitoring are key drivers of this increase in efficiency, risk defense and sustainable value creation. Together with 5G and edge computing, companies can make data-based decisions in real time and react more flexibly to external influences. The results of this work provide practical recommendations for optimizing crisis management strategies and promote the long-term resilience and sustainability of global supply chains of multinational companies.

Kurzfassung

In einer sich ständig wandelnden Welt stehen Lieferketten aufgrund von Pandemien, geopolitischen Spannungen und dem Klimawandel vor immer neuen Herausforderungen, was das Krisenmanagement in multinationalen Unternehmen vor große Herausforderungen stellt. In dieser Masterarbeit wird untersucht, wie multinationale Unternehmen durch den Einsatz nachhaltiger Praktiken in Kombination mit neuen Technologien ihre Widerstandsfähigkeit stärken und damit das Risiko ihrer globalen Lieferkette minimieren können. Darauf aufbauend werden die theoretischen Grundlagen von „Supply Chain Resilience“, Krisen- und Risikomanagement sowie die Rolle von Innovation und Nachhaltigkeit anhand der Leitlinien einer integrativen Literaturübersicht nach Snyder (2019) analysiert. Ziel war es, mit Hilfe der thematischen Analyse Schlüsselstrategien wie digitale Zwillinge, KI-gestützte Frühwarnsysteme und nachhaltige Beschaffungsprozesse und deren Zusammenspiel im Hinblick auf die Stärkung der Resilienz zu identifizieren, um sie in einem ganzheitlichen Modell zusammenzuführen. Das entwickelte ganzheitliche Modell kombiniert den Triple-Bottom-Line-Ansatz von Elkington (1997) und innovative Technologien mit dem Ziel der Krisenprävention und des Managements von Lieferkettenunterbrechungen. Die Ergebnisse zeigen, dass die Kombination verschiedener innovativer Technologien in einem digitalen Ökosystem zu einem strukturierten, branchenübergreifenden Lösungsansatz für ein zukunftsorientiertes Krisenmanagement führen kann. KI-gestützte Risikoanalysen, Blockchain-basierte Transparenzlösungen und IoT gestützte Echtzeit-Monitoring sind wesentliche Treiber dieser Effizienzsteigerung, Risikoabwehr und nachhaltigen Wertschöpfung. Zusammen mit 5G und Edge Computing können Unternehmen datenbasierte Entscheidungen in Echtzeit treffen und flexibler auf externe Einflüsse reagieren. Die Ergebnisse dieser Arbeit liefern praktische Empfehlungen zur Optimierung von Krisenmanagementstrategien und fördern die langfristige Widerstandsfähigkeit und Nachhaltigkeit globaler Lieferketten multinationaler Unternehmen.

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List of abbreviations

5G	Fifth Generation
AI	Artificial Intelligence
AI-RAN	Artificial Intelligence Radio Access Network
CBAM	Carbon Border Adjustment Mechanism
CDT	Cognitive Digital Twins
CO_2	Carbon Dioxide
CSDDD	Corporate Sustainability Due Diligence Directive
CSR	Corporate Social Responsibility
DT	Digital Twins
e.g.	Exempli gratia (« for example »)
ERM	Enterprise Risk Management
ESG	Environmental, Social, and Governance
GDPR	General Data Protection Regulation
GRI	Global Reporting Initiative
ILO	International Labor Organization
IoT	Internet of Things
JIT	Just in Time
LkSG	German Supply Chain Due Diligence Act (Lieferkettensorgfaltspflichtgesetz)
ML	Machine Learning
MNC	Multinational Corporation
OEM	Original Equipment Manufacturer
R&D	Research & Development
ROI	Return on Investment
SCM	Supply Chain Management
SDG	Sustainable Development Goals
SME	Small and Medium-sized Enterprise
TBL	Triple Bottom Line
XAI	Explainable Artificial Intelligence

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1. Introduction

In the age of a globalized world, where companies operate worldwide and rely on a network of extensive supply chains, we are constantly reminded that we live in an unpredictable and changing world (Christopher & Peck, 2004). Especially as resilience to shocks through the multilateral trading system, which reduces barriers, has also become a policy issue (Bown, 2023; Kirova, 2024). With the intensification of global competition, institutional change and low communication costs, the tendency of companies to reorganize their global value chain and shift their activities across national borders has increased significantly. This enables companies to combine the advantages resulting from specialization and increased flexibility with locational advantages. As a result, large parts of manufacturing and other more standardized activities have been relocated to emerging markets. However, recent developments have challenged these traditional distinctions between advanced and emerging economies as locations for knowledge-intensive or manufacturing-intensive activities (Baldwin, 2013). Recent research has linked the role of intra-firm relationships between various parts of the value chain. Innovative and productive activities are characterized by strong interdependencies and complementarities, and for some firms, co-location of R&D and production is crucial for development and innovation (Pedersen et al., 2017). Current industrial policies aimed at national economic growth have objectives other than increasing productivity at the firm level or spillover effects between sectors. For them, it is primarily about the resilience of supply chains, the promotion of technological progress and the need for policy makers to exercise greater control over economic activity in anticipation of potential shocks. In cross-border supply chains, governments aspire to coordinate their industrial policies with key partners without implementing measures at the national level (Bown, 2023; Kirova, 2024). This leads to the rebirth of the idea of logistic clusters, combining different partners in size with foreign trade-oriented activities and aiming for both efficiency and resilience of logistic chains (Kirova, 2024).

Supply chain disruptions can occur for a variety of reasons, with some causes occurring regularly and others being of a “one-off nature.” The severity of the impact can also vary. In recent years in particular, disruptions to the global supply chain have affected people’s daily lives. Already in the uncertain and turbulent markets of 2004, the vulnerability of supply chains has moved further up the agenda for many (Christopher & Peck, 2004). At that time, supply chains had become increasingly complex as a result of global sourcing and the ongoing trend towards leaning down (Christopher & Peck, 2004). However, the world is currently facing new challenges. Recent disruptions such as natural disasters, geopolitical tensions, labor disputes and the COVID-19 pandemic have led to severe supply chain disruptions. While climate shocks and the COVID-19 pandemic are important drivers for many modern industrial policy initiatives and have led to restructuring of supply in the markets, geopolitical conflicts and tensions, such as Russia's invasion of Ukraine and China's military activities, have created further tensions and difficulties in supply chains (Veselkovská, 2020; Bown, 2023; Kirova, 2024). In such situations, "business as usual" is often not an option, which is why supply chain managers need to rethink their strategies to achieve a high level of sustainability and resilience (Christopher & Peck, 2004; Cimino et al., 2024). For this reason, supply chain managers strive for the ideal of a complete, integrated, efficient and effective supply chain with the ability to create and maintain a competitive advantage. Accordingly, they must balance cost pressures and the need for efficiency with effective measures to manage the demands of market-driven service requirements and the known risks of routine supply chain failures (Christopher & Peck, 2004). This is sometimes challenging, as modern commercial supply chains are dynamic networks of interconnected companies and industries. "No organization is an island and even the most carefully controlled processes are only as good as the links and nodes that support them. All are dependent on efficient and reliable transportation and communication systems, a point, which is often overlooked (Peck, 2004, as cited in Christopher & Peck, 2004)."

Furthermore, the insecurity of global supply chains is increasingly masked by various resilience issues within the existing supply chain network. Therefore, supply chain resilience issues are becoming increasingly popular among researchers and policy makers. However, there is a lack of systematic research to analyze resilience problems and appropriate solution strategies in the context of global supply chains (Moktadir & Ren, 2024). However, this research is important because such supply chain disruptions are critical and can have a significant impact on companies and their crisis management, as they can jeopardize the continuity of production and access to markets.

As part of this, companies should develop and implement an effective crisis management strategy that pays sufficient attention to supply chains, leading to better flexibility and adaptability to create a competitive advantage (Veselkovská, 2020). To achieve this, it is crucial to understand the cause of supply chain problems and address them in a targeted manner. It is important to learn from a past experience as well as from current developments. This is the only way to identify and effectively implement the best solution for the various challenges. A look at the past shows that many crises follow similar patterns. An example of a pandemic that had a similar impact on the economy or was of comparable magnitude can be found at the beginning of the 20^{th} century: the Spanish flu of 1918. This devastating pandemic claimed millions of lives worldwide and changed the economy in unprecedented ways (Clay et al., 2018; Matchim, 2019; Bristow, 2013; Veselkovská, 2020). However, the economies of industrialized countries were not as closely intertwined back then as they are today, so there is no direct precedent for today’s market conditions to fall back on. Nevertheless, there have been smaller, localized disruptions in the past and their impact on supply chains has been studied. Some of the conclusions drawn from this can also be used today as a basis for analyzing the COVID-19 pandemic and its impact on the resilience and flexibility of supply chains (Veselkovska, 2020). The literature deals intensively with the effects of past disruptions and the corresponding crisis management strategies. However, it is equally important to look to the present, with a report from SAP noting that it is not always about playing defense- it is also about playing offence (*Resilient Supply Chain: The Future of Business | SAP*, n.d). Given their increasing importance, the ability of artificial intelligence and other technical tools to predict problems could be utilized. Finally, these current technologies open up new perspectives to strengthen the resilience of supply chains and ensure their sustainability in the long term without becoming dependent.

Following this introduction, the thesis will delve deeper into the theoretical underpinning and key concepts of global supply chain resilience, examining the nature of supply chain disruptions, the fundamentals of crisis and risk management, and the role of new technologies and sustainable practices in enhancing both crisis management and the overall supply chain resilience. The aim is to scrutinize which specific strategies and measures MNCs can apply to minimize the impact of disruptions in the global supply chain and which best practices can be derived from successfully implemented crisis management strategies. The focus here is on the integration of new technologies and sustainable processes to ensure long-term resilience and stability in their global supply chains. In order to do so, an integrative literature review by Snyder (2019) is used to synthesize existing knowledge, leading to a thematic analysis of technological advances in crisis management and the integral role of sustainability. Subsequently, the study explores the integration of advanced technologies and sustainability, highlighting their synergistic potential to foster resilience. This exploration culminates in the development of a holistic model grounded in the Triple Bottom Line Model, showcasing AI-supported resilience and sustainability. The thesis will conclude with a discussion of the results, addressing the research question, exploring the interactions between resilience, sustainability, and technology, and outlining the implications for both theory and practice. This comprehensive analysis of modern challenges and solutions in supply chain management will contribute to academic discussion by proving new insights into strategies, technologies, and sustainable practices. The detailed identification of risk mitigation strategies, the examination of the role of innovative technologies, and the analysis of sustainable practices broaden the understanding of how companies can effectively increase their resilience and sustainability. These contributions will offer practical recommendations for optimizing crisis management strategies and ensuring long-term resilience, promoting the integration of new technologies and sustainable practices into supply chain management, and stimulating further research and development in this dynamic area. This master's thesis thus contributes to the existing scientific literature by opening up new perspective on the complex interactions between technological innovation and sustainable practices in the context of global supply chains on the basis of an integrative analysis of current research literature. It shows how these dimensions interact to strengthen resilience and what implications this has for theory and business practice. In contrast to previous work, this study systematically combines technological and sustainability-oriented approaches in a holistic model and analyses their synergetic potential in order to design stronger supply chains.

2. Theoretical Foundation: Understanding supply chain resilience and its business impact

Globalization and digitalization have significantly increased the complexity of supply chains in recent years. Against this backdrop, supply chain management has become a key factor in the economic success of multinational companies. In addition to striving for efficiency, resilience, innovative technologies, and sustainability are increasingly becoming the focus of supply chain management. Global supply chains are therefore an integral part of modern economies and companies. However, as they become increasingly complex and dependent on international networks, they are also becoming more susceptible to disruption (Christopher & Peck, 2004; Ivanov & Dolgui, 2020). Natural disasters, geopolitical conflicts, pandemics, and other unforeseen events can have a significant impact on the stability and efficiency of these systems (Ivanov & Dolgui, 2020). Recent crises in particular have exposed the vulnerability of international supply chains and emphasized the need for robust crisis management (Chowdhury et al., 2021; Ivanov, 2021). According to the analysis of the World Economic Fund, no improvement is to be expected in the future. Their Global Risk Report of 2023 (World Economic Forum 2023, January 11, p. 7) states: "The next decade will be characterized by environmental and societal crises, driven by underlying geopolitical and economic trends."

Resilient SCM, which is characterized by the ability to react and recover quickly in times of crisis, is therefore a key focus of research (Ponomarov & Holcomb, 2009). At the same time, new technological developments, particularly the use of artificial intelligence, are becoming increasingly important. AI offers potential for optimization and early detection of disruptions, but its holistic integration into resilient and sustainable supply chain management concepts remains insufficiently researched (Waller & Fawcett, 2013; Queiroz et al., 2020). Another focus of current scientific discussions concerns sustainability initiatives in supply chains. Sustainability not only represents ethical and regulatory requirements but also influences the long-term competitiveness of globally operating companies (Seuring & Müller, 2008; Sarkis et al., 2011). Nevertheless, the integration of sustainability goals in complex supply chains continues to pose a challenge, especially in combination with technological innovations. In addition, critical tools for assessing the stability and resilience of supply chains are proving necessary in order to identify potential weaknesses at an early stage and derive suitable measures (Knemeyer et al., 2009; Ivanov & Sokolov, 2019). Existing assessment approaches often focus on sub-areas, which is why integrated models for the comprehensive analysis and management of supply chains are required to enable a better understanding of the dynamics, risks, and resilience of supply chains. A central aspect of the present work is the consideration of how modern technologies, and their interplay, can be integrated with sustainability approaches to create resilient and at the same time more environmentally friendly supply chains. The objective of this chapter is to define the theoretical foundations and key concepts that are essential for understanding supply chain disruption and its management.

2.1 Definition, structure and significance of global supply chains

In today's uncertain and turbulent markets, supply chain vulnerability has become a major issue for businesses (Christopher & Peck, 2004). The increasing complexity of global supply chains, driven by global sourcing, outsourcing, and the ongoing trend of downsizing, has significantly increased the risks and challenges for companies. They must manage disruptions caused by geopolitical events, economic instability, natural disasters, and pandemics, all of which can significantly impact supply chain performance. The challenge for modern businesses is not only to effectively manage these risks, but also to make their supply chains more resilient to ensure stability and continuity even in the face of crises (Christopher & Peck, 2004). Supply chain managers aim to build fully integrated, efficient, and effective supply chains that provide a sustainable competitive advantage. This includes balancing cost pressures with the need for efficiency while managing the complexity of market driven demand, routine outages, and external disruptions. Achieving this balance requires improved transparency, better control over internal processes, and a seamless flow of information between all supply chain stakeholders (Christopher & Peck, 2004). The ability to quickly adapt to changing conditions, mitigate risks, and recover from disruptions has become a fundamental goal for supply chain professionals. Recent studies confirm that these challenges persist. According to an analysis by Efficio Consulting (2024), companies are faced with geopolitical tensions, transportation pressures, labor and material shortages, and sustainability requirements. These factors require continuous adaptation and optimization of supply chain strategies. Additionally, a study by Schuh et al. (2017) emphasizes the importance of digitalization in supply chain management. Companies place great hopes in digital technologies to increase transparency and optimize processes. Nevertheless, fundamental challenges such as managing plan deviations and ensuring stable supply chains remain. These current sources demonstrate that the core challenges in supply chain management have remained unchanged since 2004. Companies must continue to develop strategies to ensure efficiency, transparency, and adaptability in their supply chains.

Compared to other business-related concepts, the term “supply chain” is a relatively new addition to the management lexicon. It first appeared in the early 1980s when researchers and industry experts recognized the need for an innovative approach to managing the flow of goods, information, and finances across different business functions and units (Christopher & Peck, 2004). The introduction of supply chain management (SCM) marked a move away from traditional silo operations and emphasized cross-functional coordination and integration to increase overall efficiency and customer value (Christopher & Peck, 2004). A supply chain includes all the stages directly or indirectly involved in fulfilling the customer's request. These include suppliers, manufacturers, warehouses, distributors, retailers, and end users. Supply chain management (SCM) is the strategic coordination of these elements to optimize the flow of materials, information, and finances. According to Chopra & Meindl (2001), effective SCM ensures that products reach customers in a timely and cost-effective manner, striking a balance between operational efficiency and the ability to respond to dynamic market conditions. The structure of a supply chain can be divided into three main flows:

1. Material Flow: the physical movement of raw materials, components and finished goods through the supply chain
2. Information Flow: the exchange of data between supply chain partners to facilitate coordination and decision-making.
3. Financial Flow: the movement of funds, including payments, credits, and financial transactions between different entities.

By effectively managing these flows, companies can reduce inefficiencies, minimize costs, and enhance overall supply chain performance (Mentzer et al.,2001).

2.2 Paradigm shift and associated risk in supply chain management

Over the decades, supply chain management has evolved from a purely operational function to a strategic discipline that plays a key role in determining the success of globally active companies. Considering increasing globalization, technological development and volatile market conditions, the management of supply chains has become more complex and faces new challenges (Christopher & Peck, 2004; Chopra & Meindl, 2007). The development of supply chain management encompasses a historical evolution characterized by technological innovations, changing market requirements and disruptive bottlenecks. The origins of modern supply chain management lie in the logistics of the early 20th century, where the focus was on optimizing transport and warehouse processes. In the 1960s and 1970s, inventory management and material requirement planning gained in importance, which improved the planning of material flows (Ballou, 2007). Noteworthy progress was made in the 1980s with the introduction of Enterprise Resource Planning Systems, which enabled integrative planning of resources across different business units (Chopra & Meindl, 2007). In the 1990s, globalization led to geopolitical expansion of the supply chain, because of which companies became increasingly interconnected. During this phase, the focus shifted from isolated operational processes to integrated value networks that prompted cooperation and coordination between companies (Christopher, 1998; Mentzer et al., 2001).

With falling trade barriers and lower transfer barriers, global supply chains with a clear focus on cost efficiency have emerged since the middle of the last century. The proximity to cheap production factors (especially labor) made it possible to achieve considerable cost savings, especially as the increasing standardization, for example through the introduction of containers or the spread of the English language in business communication, favored global transport. In addition, the volume-induced degression of fixed unit costs (Economies of scale) and the concentration on core competences through outsourcing (Quinn & Hilmer, 1994) promoted the trend towards global flows of goods (Peter & Rathgeber, 2017). However, practitioners and academics have also recognized two major disadvantages of global supply chains: Firstly, the risk of supply disruptions increases due to multiple interlinking of influencing factors (Tang, 2006; Wagner & Bode, 2006; Manuj & Mentzer, 2008; Peter & Rathgeber, 2017). Secondly, the global, cost-oriented supply chains are relatively inflexible due to long lead times and a lack of responsiveness to increasing product variance (customization) and volume fluctuations (volatility) (Vickery et al., 1999; Stevenson & Spring, 2007; Peter & Rathgeber, 2017). Not surprisingly, practitioners and academics have advocated for improving supply chain management as it has been identified as a lever to create and secure competitive advantage (Li et al., 2006; Peter & Rathgeber, 2017). As a result, supply chain management has constantly evolved to become not only lean but also agile and flexible (Christopher & Towill, 2001). With increasing competitive pressure, the focus is shifting (additively) from quality to cost to availability and delivery time (Christopher & Towill, 2001, as cited in Peter & Rathgeber, 2017). Although these newer, more flexible supply chains have proven to be more efficient, they are not entirely resistant to crises, as the experiences of recent years have impressively demonstrated. Supply chain disruptions can be subject to a variety of influencing factors, whether individually or in combination, which need to be identified and acted upon. The influencing factors of supply chain disruptions can be of an internal, external, or systematic nature.

2.3 Impact of supply chain disruptions on companies and the economy

Supply chain management is crucial for today's companies. It affects costs and customer satisfaction. Being able to work smoothly with different suppliers, manufacturers, distributors, and customers is key to achieving both agility and resilience in today's volatile business environment. According to Christopher (2016), agility is a critical success factor in supply chain management, which is why companies must be able to respond quickly to fluctuations in demand, supply bottlenecks and unexpected disruptions. After all, a rigid supply chain is difficult to adapt to, resulting in delays, higher costs, and customer dissatisfaction. Chopra and Meindl (2007) emphasize that companies need to implement proactive strategies such as flexible sourcing strategies, the use of digital technologies and maintaining close supplier relationships in order to minimize risk and recover effectively from disruptions. Supply chains are more connected than ever thanks to globalization. While this offers chances to cut costs and expand into new markets, it also brings challenges like political unrest, trade restrictions, and environmental concerns. Thus, proactive risk management and strategic decisions are fundamental for creating an effective supply chain management system that helps companies to overcome complexities. Good supply chain management is not just about improving daily operations; it is also about being flexible, resilient, and sustainable in the long run. In a world that feels increasingly uncertain, having a strong, adaptable supply chain is crucial for success. Companies that focus on solid supply chain strategies are more likely to handle disruptions effectively, meet what customers want, and stay ahead in today' competitive global market (Wieland & Durach, 2021).

2.3.1 Understanding the spectrum of supply chain disruptions: internal, external, and systematic factors

Supply chain disruptions occur when unexpected events affect the flow of goods, services, information, or money in a supply chain (Ivanov & Dolgui, 2020).These disruptions can originate internally or externally and last for varying lengths of time. Some cause only minor problems, while others can disrupt entire industries or economies (Craighead et al., 2007). How well a company handles these disruptions plays a critical role in its competitiveness and ability to recover. Therefore, if a company cannot respond well to these problems, it risks losing money, damaging its reputation, and sustaining long-term damage to its market position (Wagner & Bode, 2008). In a world that is becoming more and more globalized, where supply chains reach across national and international borders, managing disruptions has become a fundamental responsibility for modern businesses and the management of disruptions is therefore a core task for modern companies.

Internal factors impacting the supply chain are key aspects that can significantly affect the efficiency and stability of supply chains. Unlike external factors, which are frequently unpredictable, companies have greater control over internal factors and can implement measures to enhance resilience and flexibility of their supply chains. Inadequate inventory planning, a lack of alternative suppliers, inflexible production capacities, and poor communication and coordination are among the most significant internal factors. Insufficient inventory planning can lead to significant disruptions in the supply chain. This is often the case when stock levels do not match actual demand (Daneshvar et al., 2020). A study by Stadtler (2015) suggests that poor inventory planning is the result of deficient forecasting methods that cannot accurately predict fluctuations in demand. This leads to inaccurate order quantities, which has a negative impact on both costs and the ability to deliver. Global sourcing and single sourcing also pose major challenges for a company. Global Sourcing, the worldwide procurement of goods, has not only increased the time required, but has also made it more difficult to manage supplier relationships and secure alternative sources of supply. This entails a greater level of planning and coordination, particularly when entering markets in emerging economies like the BRIC nations (Brazil, Russia, India, China) (Scherer, 2011; Collins, 2009; Hardt et al., 2007; Kaufmann & Scherer, 2006; Kolchin & Giunupero, 1993, Gabath, 2011). Dependence on a few or even just a single supplier (single sourcing); on the other hand, represents a completely different risk. This dependency can lead to disruption of the entire supply chain if the supplier experiences problems such as production stoppage or supplier changes (Scherer, 2011; Collins, 2009; Hardt et al., 2007; Kaufmann & Scherer, 2006; Kolchin & Giunupero, 1993, Gabath, 2011). An established example is the chip scarcity that affected the automotive sector amid the COVID-19 pandemic. Numerous companies had depended greatly on a limited number of suppliers in Asia, resulting in significant production delays when these suppliers had to suspend production due to lockdowns (Shih,2020). Stiff production capacities hinder the ability to respond to demand fluctuations, such as those caused by market volatility. When demand rises or falls, companies that have inflexible production structures frequently find it difficult to scale or adjust their production. This creates bottlenecks when demand rises, or it causes overcapacity and elevated costs when demand falls. As highlighted in research conducted by Slack et al. (2013), the ability to flexibly adjust production capacity is essential for companies looking to respond to market fluctuations, and it serves as a major competitive advantage. Firms that invest into flexible manufacturing systems can adapt their production cycles faster, thereby reducing the risk of consequences of supply chain disruptions. Inefficient processes and misunderstandings can result from deficient communication and coordination within a company or throughout the supply chain. Without proper alignment among departments like procurement, production, and sales, information may not be transferred promptly, causing delays in production or delivery. According to Simchi-

Levi et al. (2014), companies that invest in integrated communication and coordination systems are better able to share information in real time and make decisions more efficiently. However, these internal factors often do not occur alone; they can occur due to or in conjunction with external factors, which are described below.

External factors that influence the supply chain include unpredictable events that are beyond the direct control of companies, which present them with major challenges and often result in serious disruptions for companies. The complexity and length of supply chains has increased due to globalization, making them more susceptible to external disruptions. The main external factors include natural disasters, geopolitical tensions, raw material shortages, transport barriers, regulatory challenges, and technological failure. Natural disasters, for example, are a significant concern. Events like earthquakes, floods, and storms are becoming more common because of climate change, and they can disrupt everything from transportation to production. For example, in July 2023, wildfires in Canada and Hawaii caused severe infrastructure damage and disrupted supply chains. Around the same time, Typhoon Doksuri brought heavy rainfall to China, severely disrupting logistics and forcing companies to pause production (Cohen et al., 2022; Obando, 2023; Everstream AI, 2023). Another striking example is the 2011 Tohoku earthquake in Japan, which led to significant production setbacks in both the automotive and electronics industries (Park et al., 2013). As climate change continues to impact the availability of critical resources such as water, metals, and agricultural products, the risk of raw material shortages increases. This further increases the pressure on global supply chains to adapt and remain resilient. The drought in Europe in 2022, for example, led to a drop in the water levels of the Rhine and Danube. This had a significant impact on shipping and transport (*Review of Maritime Transport 2022 | Navigating stormy waters*, 2022). Companies that did not implement alternative procurement strategies or layoffs suffered significant financial losses. Geopolitical issues such as political unrest, trade disputes, and armed conflicts can significantly impact supply chains. A clear example is the war in Ukraine, which demonstrated how fragile global supply chains can be in the face of political turmoil. Events like these are a strong reminder that supply chains are not only sharped by economic factors but are also highly sensitive to changes in the geopolitical environment. These events illustrated disruptions that affect different levels of the supply chain: from production stoppages and shortages of raw materials to delays in distribution and rising transport costs (Chowdhury et al., 2021).

Systematic risks in global supply chains arise from the close interdependency and dependency of various players and can lead to far-reaching chain reactions. The semiconductor shortage of 2020/2021 severely impacted various industries, including automotive and electronics, and underscored the degree of interdependence among different sectors. The container ship “Ever

Given” blocked the Suez Canal in 2021, which resulted in a considerable delay of global trade and underscored the dangers related to reliance on vital transport hubs (Christopher, 2016; Jazeera, 2021). The COVID-19 pandemic has clearly demonstrated how fragile global supply chains can be. Factory closures and transportation restrictions caused numerous problems. The increase in demand for products such as medical equipment further exacerbated the situation. Companies had to adapt their plans and processes to quickly meet public needs (Ivanov, 2021). With the ongoing digitalization of supply chains, significant risks arise from technological failures and cyberattacks. A notable example is the NotPetya cyberattack of 2017, which had a significant impact on the logistics industry and led to delays worldwide. The vulnerability of digitalized supply chains to cyber threats was highlighted by these incidents (Greenberg, 2018; Tang, 2006). Regulatory changes can ultimately exert a considerable influence on global supply chains as well. Because of Brexit, new customs regulations were established between the UK and the EU; compelling numerous companies to adjust their supply chains. The delays and cost escalations displayed the potential for regulatory changes to generate systemic risk (Christopher, 2016). To effectively manage such risks, proactive and adaptive management strategies are required to increase the resilience of the supply chain. These influencing factors that lead to disruptions in supply chains illustrate the complexity and vulnerability of global value networks. In order to meet these challenges effectively, structured approaches are needed to manage crises and minimize risks. According to Ivanov & Dolgui (2020), the viability of supply chains is determined by their ability to absorb disruptions and recover quickly. Redundancy, transparency, and flexibility play key roles here. Research suggests that in the future; companies will need to focus on risk-based approaches to minimize the damage caused by disruptive events. Strategies such as sourcing from multiple suppliers, localization, and the use of AI tools for forecasting can help keep the global supply chain stable and adaptable (Ivanov & Dolgui, 2020; Waller & Fawcett, 2013).

2.3.2 Building a resilient supply chain: The critical role of crisis and risk management

Multinational companies depend on crisis management to keep their operations running smoothly. This helps tackle unexpected events and deal with potential threats. Given the increasing interconnectedness and complexity of the global economy, these companies face a variety of challenges ranging from supply chain disruptions and natural disasters to geopolitical conflicts and cyberattacks (Christopher & Peck, 2004; Ivanov & Dolgui, 2020). Especially in times of increasing uncertainty and disruptive events, the ability to systematically manage risks and react flexibly to crises becomes a decisive success factor. Dealing with crises and risk isn’t just about damage limitation. Companies that manage risks intelligently can differentiate themselves from the competition by building strong flexible systems. This means not only taking measures to prevent problems, but also learning from past challenges and using these insights to plan for the future (Sheffi, 2007; Blackhurst et al., 2005). Multinational companies also face the challenge of implementing their risk management strategies in a dynamic environment characterized by rapid technological advancement and increasing demands for sustainability. The integration of innovative technologies and sustainable practices into crisis and risk management approaches offers a promising opportunity to strengthen the resilience of global supply chains and at the same time fulfil environmental and social responsibilities (Saberi et al.,2019; Choi et al., 2018).

Crisis management refers to the systematic planning and execution of measures designed to reduce the impact of a crisis and ensure the return to normal operations (Coombs, 2007). Conversely, Risk is understood as the potential for losses or adverse results stemming from uncertainties. Risk management involves identification, assessment, and prioritization of risks in order to subsequently take appropriate measures to mitigate them (Aven, 2015). The importance of crisis and risk management in companies should not be underestimated, especially in an increasingly globalized and dynamic business environment. Companies today face all sorts of risks, from natural disasters to economic downturns. Crisis management deals with reacting quickly when these things happen, while risk management is all about taking steps to prevent them or lessen their effects (Hillson & Simon, 2020). One of the essential elements of crisis and risk management is to incorporate these ideas into all parts of the organizational structure, including the supply chain. As supply chains are interconnected, they are particularly vulnerable to crises, meaning that if one segment is disrupted, the impact can affect the entire system. Chopra and Meindl (2016) point out that a solid risk management plan helps identify problems early, makes the supply chain more robust, and allows companies to respond quickly to unexpected events. By integrating risk management into the supply chain, companies can take measures, such as using different suppliers or adjusting their productive volumes, to reduce risks when problems occur (Christopher, 2016). Crisis and risk management are therefore not just reactive processes, but also strategic tools that ensure long-term resilience and competitiveness. In an increasingly interconnected world in which companies are heavily dependent on global supply chains, the ability to manage risks and overcome crises effectively is increasingly becoming a decisive competitive factor (Jüttner, 2005).

In order to thrive and survive in turbulent times, it is vital for MNCs to implement an effective crisis and risk management. Risk and crisis management are closely interconnected in a cyclical manner, complementing each other when addressing potential real threats to organizations. Risk management entails preventive actions to identify, evaluate and reduce potential crises (Waters, 2011), whereas crisis management is concerned with addressing disruptions that have already happened to mitigate their effects on the supply chain and facilitate a return to normal operations (Mitroff, 2004). Both methods complement each other and are essential for maintaining the resilience of the supply chain. The main objective of risk management is to reduce uncertainties and minimize the likelihood of disruptions. According to Tang (2006), it is based on the identification and assessment of risks throughout the supply chain and the application of appropriate preventive measures. While crisis management is reactive and designed to enable organizations to respond to disruptions in real time, contain them and enable rapid recovery (Ponis & Koronis, 2012). Together they build a continuous cycle which enables organizations to learn from experience and improve their resilience.

3. Theoretical Embedding: Convergence of resilience, sustainability, and technology in global supply chains

To understand the interplay of crisis management, risk management, sustainability and digital transformation, we need a solid understanding because global supply chains are becoming increasingly complex. The previous chapter highlighted the reasons for and consequences of disruptions as well as the importance of effective crisis and risk management for resilience. The current focus is on presenting fundamental theoretical concepts and frameworks that incorporate these elements into a comprehensive research approach (Sodhi & Tang, 20021). A resilient supply chain is linked to effective crisis and risk management, sustainability strategies and technological innovation and does not develop in isolation. Crisis and risk management theories form the basis for preventive and reactive strategies that aim to address uncertainties and threats in an analytical way. A strong supply chain requires sustainable practices that maintain economic, environmental, and social stability. Furthermore, digitalization helps identify risks early, optimize processes, and make the value chain more transparent (Sodhi & Tang, 2021).

This chapter introduces key theoretical concepts that are essential for understanding and analyzing resilient, sustainable, and technology-enabled supply chains. Firstly, resilience theories in supply chain management (3.1) are considered in order to understand the basic mechanisms for the adaptability of companies to uncertainties. Followed by a presentation of the concept of crisis and risk management (3.2), which demonstrates how companies systematically identify, evaluate, and control risks. The digital transformation and the emergence of digital ecosystems (3.3) form another central aspect, as modern technologies are increasingly acting as key components for resilience and sustainability. On this basis, sustainability strategies in global supply chains (3.4) are examined, focusing on long-term economic sustainability and social responsibility. Finally, a theoretical framework (3.5) is presented, which establishes the link between these three central topics and forms the structural framework for the further investigation of the thesis.

This theoretical embedding is intended to create an in-depth understanding of how companies can not only respond to current challenges but also gain strategic advantages through the targeted combination of resilience, sustainability, and technology.

3.1 Resilience theories in supply chain management

Resilience is generally defined in literature as the ability of a system to recover from disruption and return to stable state (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009). In supply chains, resilience is all about how well a network can bounce back from issues (Sheffi & Rice, 2005). A robust supply chain must be able to handle disruptions and ensure that orders are fulfilled as promised, even when unexpected events occur (Tang, 2007). Resilience theory, which has its origins in psychology (Thun-Hohenstein et al., 2020), has increasingly found its way into supply chain management in recent years. In global supply chains, resilience means the system's ability to withstand a blow, adapt, and continue operating as usual.

In supply chain management, resilience is understood as a multidimensional concept that encompasses both proactive and reactive capabilities (Drath, 2018, p.262ff.). It is about anticipating potential risks, withstanding disruptions, and recovering from them. Numerous factors play a role in this:

a) Absorptive capacity: the ability to minimize the influence of disturbances

b) Adaptability: The ability to adapt to new situations

c) Recoverability: The ability to quickly return to normal after a disruption.

The resilience theory in supply chain management emphasizes that companies should not only focus on individual resilience but must consider the entire supply chain network. This includes suppliers, customers, logistics partners and other stakeholders (Drath, 2018).

Koronis and Ponis (2018, p.33) define organizational resilience as "[…] the ability of an organizations to absorb strain and preserve (or improve) functioning despite the presence of adversity. It also refers to the ability of an organization to recover or bounce back from untoward events." This definition translates well to supply chains, which often face complex and unpredictable challenges. Supply chain management faces all sorts of disruptions like political changes, economic ups and downs, social issues, tech shifts, and environmental disasters. Companies can use resilience theory to develop plans to address these risks. The goal is to strengthen what helps us while minimizing risks. To achieve this, companies can try various strategies, such as using diverse suppliers, maintaining additional inventory, flexible production methods, establishing alternative transportation options, and leveraging real-time data and forecasts. Resilience theory in supply chain management also emphasizes the importance of learning processes and continuous improvements. Companies that learn from past crises and adapt their processes accordingly can increase their resilience over time (Berndt et al., 2024). A key aspect of strengthening resilience in supply chains is the targeted application of crisis and risk management measures. Resilience theory provides the foundational understanding of organizational adaptability and resilience, whereas crisis and risk management strategies offer practical tools for actively fostering this resilience. Companies can recognize potential disruptions early, lessen their effects, and enhance their recovery capacity through systematic risk identification, preventive actions, and effective responsive strategies (Pettit et al., 2010). The following chapter looks at how these management approaches function as an integral part of resilient supply chains and which specific measures can help to protect against uncertainties.

3.2 Crisis and risk management concepts

Crisis and risk management in supply chains have evolved considerably in recent decades to meet the growing challenges of global and complex supply chains. Modern concepts, in contrast to traditional approaches that were often reactive, and event focused, depend on proactive strategies aimed at enhancing resilience (Christopher & Peck, 2004). Previously, strategies for managing risks were mainly focused on identifying and evaluating risks that were already known. To reduce supply chain disruptions, companies depended on strategic contingency plans and safety stocks (Pettit et al., 2010). This approach often proved inadequate as it did not permit flexible adjustments to unforeseen events. One classic example is the risk management in the automotive industry in the 1990s, where companies like Toyota and General Motors depended on just in time (JIT) production to reduce storage costs. This meant that even minor disruptions, such as a fire at the supplier Aisin in 1997, led to massive production losses because there were hardly any alternative sources of supply (Jüttner et al., 2003). It was only with globalization and the growing interconnectedness of markets that it became clear that purely reactive measures were not enough. Companies often only recognized risks after disruptions had occurred and reacted with short-term solutions, which led to increased costs and a lack of flexibility (Jüttner et al., 2003). One example of this is the tsunami disaster in Japan in 2011, which caught numerous electronics and automotive companies such as Sony, Nissan, and Honda unprepared. Since many companies were dependent on a few central suppliers in the region, the sudden stop in production led to bottlenecks in the entire global supply chain (Arto et al., 2015).

A paradigm shift in crisis and risk management was brought about by the growing volatility of global supply chains. Rather than simply avoiding risk, the concept of resilience emerged, which describes the system's ability to withstand disruption, adapt and quickly restore normal operations (Ponomarov & Holcomb, 2009). This idea takes traditional risk management a step further and covers every part of dealing with risk and crises. The first phase is prevention, which is based on the early identification of potential disruptions through risk assessment and scenario analyses (Wagner & Bode, 2008). Siemens provides an example of a successful prevention strategy with its global Enterprise Risk Management (ERM), which identifies and addresses geopolitical and economic risks at an early stage (Bienert, n.d.; Revill, 2024). This is followed by the preparedness phase, in which specific emergency strategies are developed to minimize risks. These include measures such as multi-sourcing or strategic warehousing (Tang, 2006). In this context, Apple relies on a consistent diversification strategy for the procurement of critical components in order to protect itself against supply bottlenecks and reduce its dependence on individual suppliers (Collins, 2025). In the phase of coping, the focus is on the ability to react quickly and flexibly to acute disruptions. Agile decision-making processes and digital transparency are key success factors here (Scholten et al., 2014). The COVID-19 pandemic impressively demonstrated how companies such as Unilever adapted their production capacities to changing market conditions at short notice in order to avoid gaps in the supply of hygiene products (Unilever, 2020). The immediate crisis management is followed by the follow-up phase. Companies take what they learned from the crisis and use that knowledge for future plans (Blackhurst et al., 2005). For example, after Fukushima disaster in 2011, Toyota addressed supply chain problems by building a diverse supplier network to better prepare for future problems (Williams, 2021). While older methods such as additional inventory or just-in-time production tended to focus on quick solutions, companies today tend to rely on technology-driven and team-oriented strategies. With the help of new technologies, preventive measures, and cooperative strategies, companies can deal with immediate disruptions and also ensure their long-term competitiveness.

3.3 Digital transformation and ecosystems in supply chains

By incorporating automation and processes driven by data, digital transformation has brought about fundamental changes in supply chain management. With this change, companies can enhance the efficiency and transparency of their supply chains (Ivanov & Dolgui, 2021). In the context of SCM, digital transformation relates to the incorporation of advanced technologies for process optimization, enhancement of efficiency, and greater transparency within the supply chain (Queiroz et al., 2021). Companies can leverage real-time data for informed decision-making and enhanced competitiveness by utilizing technologies like the Internet of

Things (IoT), artificial intelligence (AI), and big data analytics (Kache & Seuring, 2017). This results in enhanced management of logistics processes, diminished uncertainty, and a quicker reaction to market fluctuations. The 1970s saw the emergence of electronic data processing systems for order management and inventory control, marking the start of digitalization in logistics (Christopher, 2016). The introduction of the Internet in the 1990s made electronic data transmission and online tracking feasible, enhancing transparency and efficiency within the supply chain (Waller & Fawcett, 2013). Since the 2010s, IoT, AI and blockchain technologies have further increased the level of automation and now enable data-based decisions in real time (Ivanov et al., 2019).

A central element of digital transformation in supply chain management (SCM) are digital ecosystems characterized by platform economics, increased transparency, and data-driven decision management. Digital Platforms like SAP Ariba and TradeLens have become key intermediaries linking different participants of the supply chain. They facilitate real-time information exchange, foster collaboration, and lower transaction costs (Papadopoulos et al., 2021; Van Hoek,2020). According to Van Alstyne et al. (2016), business models built around platforms boost efficiency by centralizing data regarding supply, demand, and delivery capacity. This consolidation allows for the optimization of supply chain management. Supply chain visibility, made possible through digitalization, is another vital factor. It guarantees complete transparency throughout the whole supply chain. Real-time tracking of goods movements and inventory monitoring using IoT sensors and RFID (Radio Frequency Identification) technologies improve the control of logistics processes (Ben-Daya et al., 2019). This improved visibility helps to identify potential bottlenecks early and create resilient supply chains, as companies can react more quickly to unexpected disruptions (Wieland & Durach, 2021). In addition to increased transparency, data-driven decision management also plays a crucial role in modern SCM. The use of predictive analytics and AI-supported analytics enables companies to predict future demand developments and plan their resources efficiently (Choi et al., 2018). This leads to optimized warehousing, reduced costs, and higher customer satisfaction, as companies are able to make precise forecasts about sales markets and logistics flows (Dubey et al., 2020). In particular, the use of machine learning algorithms improves forecast accuracy and minimizes risks in the supply chain by recognizing patterns in enormous amounts of data and alerting companies to potential disruptions at an early stage (Wamba et al., 2017).

Even with the main benefits, digital transformation in SCM also introduces challenges. As sensitive information must be safeguarded against unauthorized access, data protection and IT security are crucial components. Especially for small and medium-sized companies, high investment costs for implementing recent technologies pose a challenge (Tang & Veelenturf, 2019). Moreover, to utilize the new technologies effectively, it is necessary to adapt organizational structures and processes and provide extensive training for employees (Sharma et al.,2024). This means that while digitalization allows for considerable enhancements in supply chain efficiency and transparency, it is not enough on its own to guarantee long-term stability and competitiveness. Along with technological innovations, ecological and social factors must also be incorporated into supply chain management. Aspects of sustainability, including fair working conditions, reduction of CO_2 emissions, and resource-conserving product processes, are equally crucial. Firms that depend solely on digital transformation while neglecting sustainable and resilience-focused strategies face the danger of regulatory and reputational drawbacks, as well as heightened susceptibility to crises and external shocks. To achieve a full perspective on the supply chain, it is necessary to integrate digitalization with sustainable and responsible business models.

3.4 Sustainability goals in global supply chains

Sustainability has become a central guiding principle in supply chain management (SCM) in recent decades. Companies are increasingly under pressure not only to maximize economic efficiency, but also to assume ecological and social responsibility (Seuring & Müller, 2008). While traditional approaches often viewed corporate social responsibility (CSR) as a voluntary additional measure, sustainability is now an integral part of strategic corporate decisions (Pagell & Wu, 2009). The Triple Bottom Line (TBL) model is particularly useful in this context, since it includes not only economic but also ecological and social aspects of corporate management (Elkington, 1997). In contrast to Environmental, Social and Governance (ESG) criteria, which primarily serve as a benchmark for investors, TBL focuses on holistic value creation along the entire supply chain (Montiel & Delgado-Ceballos, 2014).

The integration of sustainability into supply chains has developed over several phases. Originally, environmental, and social aspects were hardly the focus of supply chain management, as economic optimization and cost reduction were the main focus (Carter & Easton, 2011). In the 1990s, the transition from CSR initiatives to more sustainable business models began, reinforced by societal pressure and stricter regulatory requirements (Koplin et al., 2007). The adoption of the UN Sustainable Development Goals (SDGs) in 2015, in particular, helped companies to strategically enhance the sustainability of their supply chains (*Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs*, n.d). Modern sustainable supply chains extend beyond voluntary CSR measures and are frequently embedded within corporate strategy. Firms are coming to understand with growing frequency that sustainable practices in procurement and production can lower regulatory risks while also offering a competitive edge (Genovese et al., 2017).

An important element of sustainable supply chains is the reduction of their ecological footprint. To reduce waste and recycle materials, businesses are turning to the circular economy with growing frequency (Lieder & Rashid, 2016). Strategies such as recycling, resource-efficient production processes and sustainable procurement play a leading role in this (Geissdoerfer et al., 2017). One example of this is Unilever, which was able to significantly reduce its CO_2 emissions through sustainable material procurement (Carter & Rogers, 2008). In addition to the circular economy, emission reductions through more efficient transport routes, alternative packaging materials and renewable energies are also becoming increasingly important (Golicic & Smith, 2013).

In addition to ecological aspects, the social dimension plays a crucial role. Efforts aimed at fair trade and adherence to global labor standards help enhance working conditions throughout international supply chains (Barrientos et al., 2011). Firms are more and more required to avert human rights abuses and child labor within their supply chains, particularly due to regulations like the German Supply Chain Due Dilligence Act (LkSG) and the British Modern Slavery Act (Schleper et al., 2017). Patagonia is considered an example of best practices in the area of social sustainability because the company promotes transparency in its production processes and sets high social standards for its suppliers (Krause et al., 2009).

Sustainability is not only an ethical obligation, but also an economic necessity. Companies that invest in sustainable supply chains benefit in the long term from more stable raw material prices, lower regulatory risks, and stronger customer loyalty (Tukamuhabwa et al., 2015). In particular, the reduction in resource consumption and more efficient transport routes lead to cost savings and increased crisis resilience (Christopher & Holweg, 2011). At the same time, however, companies face the challenge of making sustainable measures economically viable, especially when short-term investment costs are high (Pagell & Wu, 2009).

Despite the many benefits, companies face significant challenges in implementing sustainable practices in their supply chains. One of the biggest hurdles is the high initial investment required for sustainable production technologies, emission reductions or fair wages (Beske & Seuring, 2014). In addition, there is often resistance within the organization, especially when short-term profit goals are at the forefront (Ghadge et al., 2020). Another challenge comes from the regulatory landscape: legal requirements are constantly evolving, and international standards frequently lack consistency. Transparency, resource efficiency, and emission reduction are ways in which digitalization can act as a vital impulse for sustainable supply chains. With technologies like blockchain, IoT, and AI companies can monitor and enhance environmental and social standards more precisely (Krings & Schwab, 2020). However, sustainable supply chains need more than just technological solutions; they require a strategic integration of environmental, social, and economic principles.

3.5 Theoretical Framework

Incorporating new technologies and sustainability strategies into the supply chain could greatly enhance efficiency and resilience. Progress in technologies like AI, blockchain, and IoT allows for more accurate tracking, forecasting, and management of supply chain activities. Simultaneously, sustainable practices offer a structure for tackling environmental and social issues throughout the value chain, particularly as these challenges are recognized as more significant in contemporary society than they were previously (Ivanov & Dolgui, 2020; Carter & Rogers, 2008).

New technologies could make a direct contribution to promoting sustainability goals by improving transparency and efficiency. AI-supported forecasting systems, for example, enable the prediction of supply chain disruptions and the optimization of resource flows. According to Dubey et al. (2020), the integration of AI into supply chain processes has led to a reduction in waste and better alignment with environmental standards. At the same time, blockchain technologies can be used to verify the origin of raw materials and ensure compliance with social and environmental standards (Saberi et al., 2019). Sustainability should benefit from digitalization through the ability to analyze data in real time and automate decision-making processes. As an illustration, the IoT allows for ongoing surveillance of manufacturing operations and logistics pathways. This not only boosts efficiency but also lowers emissions (Genovese et al., 2017). Firms like Maersk have created digital platforms that leverage real-time data to enhance fuel efficiency and lower CO_2 emissions. Even with the possible synergies, it is challenging to carry out technological and sustainable measures simultaneously. High initial investments in technologies and sustainable infrastructures can be challenging for companies, especially for SMEs (Pagell & Wu, 2009). Moreover, the adaptation of new technologies into current systems may restrict the supply chain's ability to adapt and innovate. The literature emphasizes various facets of advanced technologies and sustainability regarding supply chain resilience, yet one crucial area is overlooked: the potential synergy that arises from merging the incorporation of advanced technology systems with sustainability initiatives in relation to supply chain resilience within crisis management. Present research often considers either the role of technology in addressing supply chain or the use of sustainable practices, but rarely both approaches (Tukamuhabwa et al., 2015).

4. Research process and methodology

This chapter outlines the methodological research process of this thesis. Firstly, the choice of an integrative literature review as the research design is justified in order to systematically answer the research question. This method makes it possible to bring together findings from different theoretical and empirical sources and thus gain a comprehensive understanding of the subject of research. Building on this, the methodological principles of integrative literature research according to Snyder (2019) are described, including the search strategy, the selection criteria, and the synthesis of the results. A central component of this process is the development of a holistic model that is derived from the identified literature results. The modelling is carried out by thematically analyzing and synthesizing the existing research and serves to provide an overarching perspective on the topic. Finally, the methodological approach is critically reflected upon. The aim of this reflection is to make methodological decisions transparent and to discuss possible limitations of the integrative literature review - particularly with regard to the completeness of the literature selection and the subjective interpretation in the modelling.

4.1 Choice of research design

The study adopted the research design of an integrative literature review, as per Snyder (2019). This approach allows for a thorough synthesis of theoretical and empirical findings across different fields of research and is especially appropriate for examining complex, multidimensional subjects. The thesis addresses the incorporation of AI technologies and sustainability efforts into global supply chain crisis management, making an integrative literature review suitable for uniting various research standards and including interdisciplinary perspectives. In addition, it is particularly suitable for expanding existing theories and concepts. The aim of this work is not only to analyze existing strategies, but also to integrate innovative approaches, particularly the combination of advanced digital ecosystems with sustainable objectives in crisis situations. The methodology allows for the combination of theoretical, conceptual, and empirical work, enabling a deep understanding of the research subject (Torraco, 2005). Furthermore, it is particularly suitable for expanding existing theories and concepts. The aim of this work is not only to analyze existing strategies, but also to integrate innovative approaches, in particular the combination of advanced digital ecosystems with sustainable objectives in crisis situations. The methodology allows for the combination of theoretical, conceptual, and empirical work, enabling a deep understanding of the research subject (Torraco, 2005). A further characteristic of this method is its exploratory nature. While systematic reviews would apply strict inclusion and exclusion criteria, thereby excluding potentially relevant but less established studies (Levy & Ellis, 2006), the integrative literature review offers the opportunity to consider non-traditional sources such as case studies or practice-orientated reports. For a dynamic research area like the integration of AI and sustainability into supply chains, this is valuable because it brings practical insights and new technological advancements into the analysis. Thus, the integrative literature review can provide the necessary conditions for adequately addressing the research question posed in this thesis. It allows for interdisciplinary analysis, theory-based synthesis of existing research, and the creation of new conceptual approaches that are scientifically valid and practically relevant.

4.2 Methodological framework according to Snyder (2019)

According to Snyder (2019), the integrative literature review is a recognized method for systematically compiling and analyzing various theoretical perspectives and empirical findings. This approach is especially appropriate for research questions that necessitate an interdisciplinary, thorough, and adaptable synthesis of the existing literature (Snyder, 2019). Unlike strictly systematic or semi-systematic literature reviews, an integrative literature review permits a broader consideration of heterogeneous sources, which is essential for investigating complex and dynamic topics (Torraco, 2005).

4.2.1 Relevance of the method for the research question

An integrative literature as the methodological approach was selected, as recommended by Snyder (2019), because of the complexity and interdisciplinary nature of the research question. The investigation of how multinational companies can integrate new digital ecosystems into their crisis management in order to minimize global supply chain disruptions, promote sustainability goals and increase resilience requires a complete view of different research strands. The integrative literature review provides an optimal basis for this, as it enables the synthesis of different theoretical, empirical, and conceptual work and thus creates a deep understanding of the research problem (Snyder, 2019). The research question of this thesis touches on several academic disciplines, including supply chain management, crisis management, digital transformation, and sustainability research. While a systematic literature review could provide a comprehensive overview of existing work in these individual areas, it would potentially exclude innovative or interdisciplinary approaches due to strict inclusion and exclusion criteria (Tranfield et al., 2003). The integrative literature review, on the other hand, allows the flexible consideration of heterogeneous sources and helps to identify existing research gaps as well as to link theoretical perspectives from different disciplines (Torraco, 2005). A broader approach is particularly necessary for emergent topics such as the integration of new digital ecosystems into crisis management. These technologies have the potential to make global supply chains more resilient (Ivanov & Dolgui, 2020), but their integration is associated with challenges that are not only technical, but also organizational, ethical, and environmental in nature (Queiroz et al., 2020). The integrative literature review makes it possible to integrate these different dimensions into a complete analysis approach. A central aspect of the research question is the linking of crisis management with sustainability goals - an area that has so far only been considered fragmentarily in scientific literature (Chowdhury et al., 2021). While some studies analyze the role of resilient supply chain strategies (Sheffi, 2020), others focus on sustainability integration in supply chains (Seuring & Müller, 2008). However, only a few studies analyze how new digital technologies can simultaneously contribute to crisis management and the promotion of sustainability goals, especially since these can be interrelated (Köhler & Pizzol, 2020). The integrative literature review offers a methodological advantage here, as it brings together different research perspectives and identifies overarching patterns (Whittemore & Knafl, 2005). This not only expands the knowledge base on existing concepts and theories, but also allows potential synergies between crisis management, digitalization, and sustainability to be identified. Another key objective of this work is to develop a theoretical model that describes the interaction between digital ecosystems, crisis management and sustainability goals. This is a key strength of the integrative literature review, as it not only brings together existing knowledge, but also develops new conceptual frameworks (Torraco, 2016). The results obtained through the analysis are intended to map the challenges and opportunities of integrating new technologies into global supply chains and provide practical implications for multinational companies. This is particularly relevant because traditional crisis management approaches are often one-dimensional and do not systematically consider digital technologies and sustainability aspects (Dolgui et al., 2020). Due to its iterative nature, the model can be continuously reflected and further developed on the basis of new scientific findings. This ensures that the work not only provides an inventory of existing research, but also theoretical innovations.

4.2.2 Delimitation of the integrative literature review

The integrative literature review according to Snyder (2019) differs significantly from other approaches to literature research, in particular systematic and semi-structured reviews, as well as from empirical research methods. The choice of this approach for the present work allows for the synthesis of various theoretical and empirical perspectives and makes it especially appropriate for examining complex, interdisciplinary issues. In accordance with Tranfield et al.

(2003), systematic literature reviews follow strictly defined inclusion and exclusion criteria, as well as comprehensive coverage of the relevant literature on a specific research question. This approach is especially appropriate for meta-analyses of research areas with a solid theoretical framework. Conversely, the integrative literature search provides a broader methodological openness and allows for the inclusion of heterogeneous sources that may be excluded in a systematic review. Another important distinction concerns the objective: systematic reviews seek to create a precise catalog of the existing literature, whereas integrative literature reviews are more oriented toward theory development and the conceptualization of new perspectives (Torraco, 2005). This makes it especially useful for research inquiries probing into emergent phenomena, novel technologies, or interdisciplinary settings, like the connection between new technologies and sustainability concerning MNC's crisis management during supply chain disruptions in this thesis. The semi-structured literature search represents a middle ground between the systematic and the integrative literature search. It is often used in interdisciplinary studies, whereby a certain degree of flexibility is maintained. However, theoretical, or thematic guidelines are usually defined in order to narrow down the selection of literature (Wong et al., 2013). The main difference to the integrative literature search lies in the adaptability during the research process: While semi-structured reviews often follow a fixed strategy, the integrative approach allows for an iterative adaptation of the search strategy and the continuous inclusion of new concepts as soon as new findings emerge from the analysis. This dynamic is essential for developing the holistic model presented in chapter 6, as it facilitates the ongoing synthesis of new perspectives. Unlike empirical methods that rely on primary data (such as interviews, experiments, or surveys), integrative literature research is dedicated solely to the analysis and synthesis of existing literature. It is thus especially appropriate for identifying existing knowledge gaps in, advancing theories, and crafting conceptual models. Integrative literature reviews, as described by Snyder (2019); concentrates on critically reflecting and recontextualizing existing findings, in contrast to empirical methods, which seek to generate new data. This is particularly relevant for the investigation of emergent trends, as a lot of relevant information is already available in the form of studies, reports, and case analyses.

4.2.3 Search strategy and source base

The development of a sound search strategy is a crucial step in the integrative literature search. Although an integrative literature review aims to combine different perspectives and sources into a comprehensive overall picture, a systematic search strategy is nevertheless essential. A systematic approach ensures that the research remains comprehensive and comprehensible and that the research question can be answered in a well-founded manner. For this reason, the literature search is conducted in four clearly defined phases: Design, Conduct, Analysis and Structuring. Each of these phases contains specific steps that ensure that relevant studies are identified, critically analyzed, and structured in a meaningful way. This methodical approach prevents important sources from being overlooked or the results from being distorted. A structured search thus strengthens the validity of the integrative literature review and enables a well-founded synthesis of the available findings.

Phase 1: Design

In the initial phase of the literature search , the focus is on creating a structured framework that guarantees a systematic and targeted search for relevant literature. This framework encompasses the specification of the research question, definition of the research scope, identification of central main topics and key terms, and formulation of the search strategy. This phase is iterative, which means that continuous adjustments are made throughout the research process to ensure the relevance, timeliness and quality of the literature reviewed. In order to clearly define the scope of the literature search, the research question was formulated precisely:

„How can the crisis management of multinational companies integrate digital ecosystems not only reduce the impact of global supply chain disruptions but also to promote sustainability goals and increase resilience?"

This research question requires an interdisciplinary approach, as it touches on various fields of research, including crisis management, digital ecosystems, sustainable supply chains and resilience. It is therefore essential to clearly define the thematic focus and identify the most important aspects to be analyzed in literature. Based on the research question, four overarching topics can be derived, which form the basis for the literature review:

1. Crisis management in multinational companies
    - Strategies and best practices in crisis management
    - Impact of global supply chain disruptions on MNCs
    - Crisis prevention and response in global supply chains
2. Digital ecosystems and new technologies
    - Role of digital ecosystems in the resilience of global supply chains
    - Applications of AI, blockchain, IoT and other advanced technologies in supply chain management
    - Synergies between new technologies and crisis management strategies
    - Digital solutions to promote sustainable supply chains
3. Sustainability in global supply chains
    - Integration of TBL criteria
    - Impact of global crises on sustainable supply chain strategies

- Digital solutions to promote sustainable supply chains

4. Resilience of supply chains
    - Concepts and models for increasing resilience
    - Digital transformation as an enabler for resilience
    - Long-term adaptation strategies for robust supply networks

Based on the main topics identified, relevant keywords and their possible variations or abbreviations are defined. These serve as search terms for systematic searches in scientific databases. A targeted combination of these terms enables a broad yet focused coverage of the relevant literature.

Table 1: Keywords

Crisis Management	Supply chain risk management, disaster recovery in supply chains
Digital ecosystems	Emerging technologies, AI, blockchain, digital twins, 5G , Cloud Computing,…
Sustainability	Green supply chain management, TBL integration, (ESG-Integration)
Supply chain resilience	Supply chain agility, risk mitigation strategies
Multinational companies	MNCs, global business networks, multinational corporations

Boolean operations (Boolean operators), truncations and phrase searches are used to maximize the search results:

- ("crisis management" OR "risk management") AND ("multinational company*" OR MNC* OR "global supply chain*") AND ("disruption*" OR "resilience*")
- ("digital ecosystem*" OR "digital technology*" OR "digital platform*") AND ("supply chain*" OR "logistic*") AND ("AI" OR "blockchain" OR "IoT" OR "big data")
- ("sustainability" OR "green supply chain management") AND ("ESG" OR "TBL integration") AND ("supply chain*" OR "logistic*")
- ("supply chain resilience" OR "risk mitigation") AND ("global supply chain*" OR "multinational company*") AND ("digital technology*" OR "AI" OR "cloud computing")

The search strategy includes the systematic identification of relevant literature sources. Several scientific databases and search engines are used to ensure comprehensive coverage, like Web of Science, Scopus, Google Scholar, and the University Library. To ensure the relevance of the search results, clear inclusion and exclusion criteria are:

Table 2: Inclusion & Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Peer-reviewed scientific articles and conference papers	Articles with a primary focus on industries outside of supply chain management
Publications from the last 15 years	Publications that focus only on national or regional supply chains with no global reference
Studies focusing on crisis management, digital ecosystems, sustainability, or resilience in global supply chains	Blogs, opinion articles, popular science reports
Works with empirical or conceptual relevance to the research topic	<2010, exception Elkington, 1997
Grey literature such as reports from international organizations or company reports, as far as these provide relevant insights.	

Moreover, a snowball method (Backwards & Forwards Citation Tracking) is employed to find additional articles. This entails verifying the references lists of extensively cited research and examining which newer studies cite this research. Throughout the research process, the search strategy is regularly assessed and adjusted. If it turns out that certain terms or databases provide results that are not sufficiently relevant, the search terms are redefined or alternative databases are included. In addition, the search results are constantly reviewed and revised to ensure that no important studies have been overlooked. This research targets stakeholders from both academic and practice-oriented backgrounds that want to gain knowledge about incorporating innovative technologies and sustainability into worldwide supply chains. On a practical level, it is aimed in particular at executives of multinational companies, decision-makers in supply chain management as well as innovation and sustainability managers who are looking for effective strategies to utilize digital ecosystems for crisis management, increasing resilience and sustainable corporate management. It is thus expected that the insights acquired will serve to advance theoretical concepts as well as to put into practice innovative approaches to crisis management.

Phase 2: Conduct

The second phase of the search strategy consists of carrying out the literature search, systematically selecting valuable articles, and documenting the entire search process to guarantee transparency, reproducibility, and traceability. This is necessary for ensuring the scientific quality of the integrative literature review and allow for critical reflection on the methodology (Snyder, 2019). Even though an integrative literature search offers more flexibility than a systematic literature review, it still requires a systematic search strategy to ensure a comprehensive and objective analysis of the field of research. The systematic approach helps to minimize bias, ensure the quality of the studies included, and guarantee a broad interdisciplinary perspective. An unsystematic or selective search can cause relevant studies to be missed or favored, leading to a limited or one sided representation of the research state (Boell & Cecez-Kecmanovic, 2015). Through the systematic approach of an integrative literature review it is possible to further develop the research question based on data and generate new theoretical perspectives (Snyder, 2019). A structured and transparent approach is essential to ensure the reproducibility of the literature search.

The studies are selected in several steps to ensure a high-quality and well-founded basis for the integrative literature search. Firstly, an initial filtering is carried out based on the previously defined inclusion and exclusion criteria. For example, only articles released after 2015 are considered, while works without sufficient empirical or theoretical relevance are excluded. According to Tranfield et al. (2003), the funnel method helps to make the search process more efficient. It starts with a wide search to gather as much relevant literature as possible. Then, title and abstracts are reviews to filter out studies that aren't relevant. In the next step, the remaining studies are read in full and analyzed in detail in order to make a final decision on their inclusion. The PRISMA Flow Chart (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) according to Moher et al. (2009) is used to document the selection process more transparently. This chart visualizes the various selection stages of the literature search and provides a clear overview of the entire process. The PRISMA documentation comprises the following steps: (1) Identification of the studies originally found, (2) screening, in which non-relevant articles are excluded after an initial review of the title and abstract, (3) eligibility, in which a detailed full-text analysis is carried out, and finally (4) inclusion, in which the final studies for the analysis are determined (Figure 1). By systematically documenting and visualizing the process with PRISMA, we can guarantee that the selection process adheres to methodological rigor, transparency, and reproducibility. This helps to reduce bias and ensure the scientific integrity of the integrative literature search.

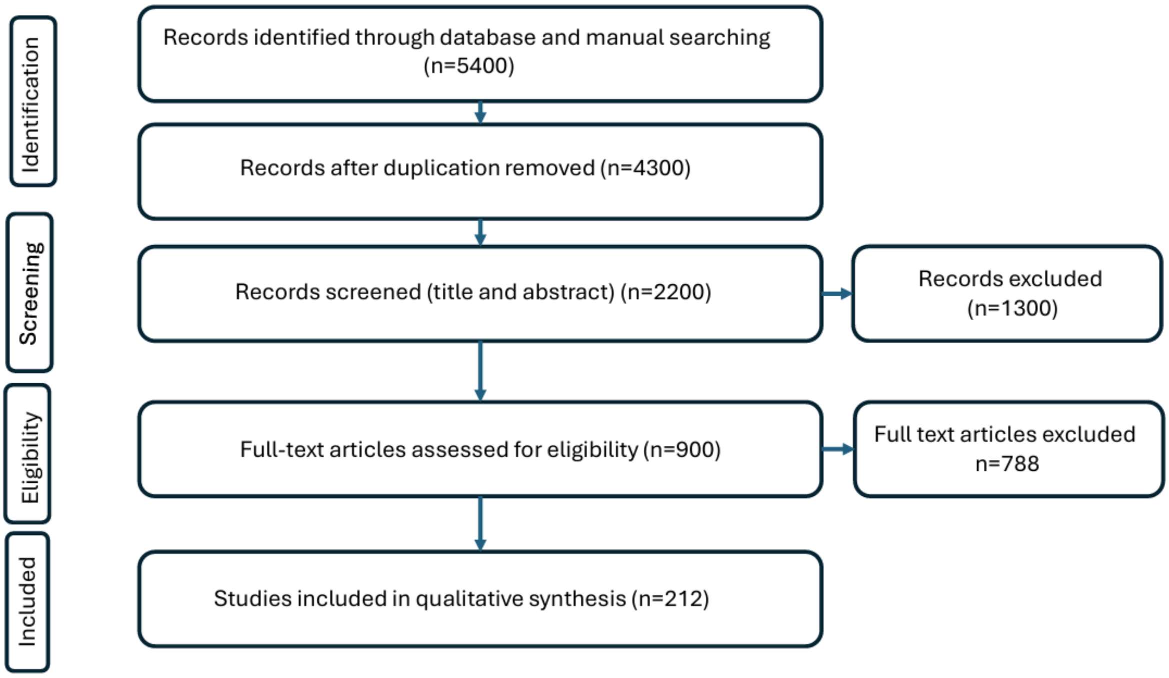

Figure 1: PRISMA Diagram (Own illustration but based on the template of Moher et al., 2009)

Once the relevant literature had been identified using the PRISMA diagram, further research was carried out using forward and backward citation tracking. By analyzing the citations within the selected studies (backward citation), further central works relevant to the research field were found. At the same time, forward citation was used to identify more recent publications that refer to the selected studies and thus highlight current developments in the field of research. This additional search method made sure that no significant contributions were overlooked and that the integrative literature search provided as complete and well-found picture as possible of the existing scientific findings.

Phase 3: Analysis

The third phase of the integrative literature review involves a systematic analysis of the reviewed and selected literature. This step involves extracting key topics, concepts, and findings from the relevant studies and organizing them systematically. This phase aims to organize the current knowledge, determine the primary research topics, and pinpointed existing research gaps (Snyder, 2019). A central component of this phase is data extraction, in which both theoretical models and empirical studies are taken into account. The extracted information is then analyzed thematically in order to identify common patterns, correlations, and differences between the studies. This is structured along the previously defined main themes:

- Crisis management in multinational companies

- Digital ecosystems and new technologies
- Sustainability in supply chains
- Resilience of supply chains

By iteratively coding the literature, the findings are assigned to these categories (see Appendix) so that overarching trends and gaps in knowledge can be identified (Braun & Clarke, 2006). A particular challenge here is the synthesis of heterogeneous research approaches - integrative literature analyses work with a variety of theoretical and empirical sources, which is why careful coordination of content is required (Whittemore & Knafl, 2005). An essential aspect of the analysis is the quality assurance of the studies used. The reliability, validity, and methodological rigor of the respective studies were taken into account (Snyder, 2019). This guarantees that the results acquired from the literature are reliable and provide a strong foundation for the synthesis. Ultimately, the results are aligned with the research question to guarantee that every aspect has been thoroughly taken into account. Based on this analysis, a holistic model is developed that describes the integration of digital ecosystems into the crisis management of multinational companies. This model combines existing theories with empirical findings and integrates new, forward-looking perspectives to promote sustainability and resilience (Torraco, 2005). The thematic analysis contributes to synthesizing existing research and providing a clear overview of the connections between digital ecosystems, crisis management, and sustainable supply chains. This highlights the challenges and opportunities that arise from integrating new technologies into strong and sustainable business practices.

Phase 4: Structuring and Writing

The last step of the literature review is about putting everything together and writing it all down. This part is really important because it makes sure the research results are structured in a clear and logical way. The goal is to showcase the extracted information in a clear, organized narrative while situating it within the broader context of the research question. A vital initial measure during this phase is to establish a clear structure for how the results will be presented. This is done in close coordination with the main topics identified in the analysis phase, which must be organized and hierarchized thematically. A clear line of argumentation helps to present the central aspects of the research in an understandable way and to ensure consistency of content. A topic-centered structure is chosen in which the main topics of the work - crisis management, digital ecosystems, sustainability, and resilience - are clearly differentiated from each other, but at the same time presented in their interdependence. This structure enables a fluid development of the argumentation, starting with an introduction to the respective topic, through the presentation of relevant research results, to the synthesis and discussion of the findings. It’s really important to organize the topics so the reader can easily follow along with the research. Once the content is structured, a clear narrative emerges that concisely summarizes the results of the literature review and places them in the context of existing research. It is crucial to systematically integrate both theoretical and empirical findings in order to demonstrate the relevance of the results to the research question. The synthesis of the findings takes several aspects into account:

- Linking theories and empirical evidence: Research findings are related to established theories to emphasize their scientific validity
- Identification of research gaps: The open questions and blind spots in the existing literature identified in the analysis are highlighted
- Discussion of the practical and scientific implications: In addition to the theoretical relevance, the practical consequences of the results for companies and political actors are also worked out

It is particularly important in this phase that the arguments are logically linked, and that the reader is led to the answer to the research question through a coherent presentation of the results (Torraco, 2005). Another central component of this phase is the review of the scientific quality of the presentation. The work is regularly evaluated for clarity, coherence, and academic rigor. This includes, among other things:

- Linguistic precision and comprehensibility
- Compliance with academic standards
- Logical consistency and stringency of the argumentation

In addition, a peer review or feedback round can be conducted in order to obtain external assessments of the quality and comprehensibility of the text. Once the phase is over, the entire text is reviewed and revised. The completeness and consistency of content, as well as formal aspects, are verified. This encompasses correcting linguistic and stylistic mistakes, verifying citations and references, and ensuring the structure of the argumentation aligns with the research question. The thesis is finalized and prepared for submission only after the final revision. During this phase, the clarity and methodological rigor of the research results are guaranteed, in addition to their scientific validity (Torraco, 2005; Snyder, 2019).

4.3 Methodological model development through integrative literature research and iterative extension of the triple bottom line approach

The theoretical foundation of the development is based on an adaptation and extension of existing concepts in order to take into account new scientific and practical challenges in the areas of crisis management, digital transformation, and sustainability. The methodological approach is based on established approaches to develop scientific literature. In particular, three central theoretical principles can be identified that guide the modelling process in this work, which are the theoretical adaptation according to Gregor (2006), the concept of integration according to MacInnis (2011) and the framework transfer according to Eisenhardt and Graebner (2007).

The first methodological basis is the theoretical adaptation according to Gregor (2006), which describes how existing models and theories can be adapted to changing framework conditions to generate new scientific findings. The TBL Model (Elkington, 1997) serves as an established theoretical framework for the integration of sustainability into business processes. However, it does not take into account the challenges of digital transformation or its potential to increase the resilience of global supply chains. The adaptation of the model in this theses therefore follows the principle of extending and existing theory by integrating digital ecosystems as additional influencing factors. Gregor (2006) argues that such an approach is particularly suitable when an existing model is be retained in its basic structure but expanded by new perspectives. The combination of TBL with digital technologies and crisis management thus creates a new theoretical basis that goes beyond the original model structure, but builds on it.

The second component is the model adaptation through concept integration, as described by MacInnis (2011). This approach emphasizes that theoretical models can be further developed through the targeted inclusion of new concepts in order to answer complex, interdisciplinary research questions. In this thesis, the TBL model is conceptually extended by integrating digital ecosystems and resilience factors. Findings from digitalization research, supply chain management and crisis management are systematically linked with sustainability perspectives. MacInnis (2011) argues that such concept integration is particularly useful when the new elements are not only complementary but also transformative for the existing model. The integration of digital technologies into the TBL model not only leads to an expansion of existing dimensions, but also changes the way in which resilience and sustainability can be conceptualized in a corporate context.

In addition to theoretical adaptation and concept integration, the model developed is also based on the principle of framework transfer, as described by Eisenhardt and Graebner (2007). This approach deals with the question of how established theories and models can be transferred to new areas of application in order to test their validity in changed contexts. In this paper, the TBL model originally developed for sustainability management is transferred to crisis in supply chains. The digital transformation requires an adaptation of the classic sustainability dimensions, as ecological and social aspects are increasingly influenced by technological innovations. Eisenhardt and Graebner (2007) argue that such a framework transfer is particularly useful if the theoretical concept enable a new perspective on existing challenges and at the same time offer the possibility of deriving new hypotheses for future research.

The methodological approach to model development is based on dynamic further development of existing theoretical concepts. By combining the theoretical adaptation to Gregor (2006) , the concept integration according to MacInnis (2011) and the framework transfer according to Eisenhardt & Graebner (2007), the triple bottom line model was systematically expanded to reflect the role of digital ecosystems and the importance of resilience for sustainability management in global supply chains. This combination of methods not only provides a sound theoretical basis, but also helps to close a research gap at the interface of sustainability, crisis management and digitalization.

4.4 Challenges and quality criteria

Conducting an integrative literature review according to Snyder (2019) as part of this thesis is a demanding process that poses both methodological and content-related challenges. In particular, the complexity of the topic - the integration of new digital ecosystems into the crisis management of multinational companies to promote sustainability and resilience - requires broad-based and interdisciplinary research. This makes it necessary to combine different strands of research while ensuring high scientific quality standards. A key challenge of this work is the diversity and heterogeneity of sources. Due to the economic, technological, and sustainability-related facets of the topic, it is essential to include studies from various disciplines. Insights from supply chain management, crisis management research, digital transformation, and sustainability science must be integrated. Each of this fields has its own theories, methods, and definitions, requiring careful categorization and synthesis of the literature (Snyder, 2019; Torraco, 2005). Another challenge is the rapid development of the research field. New studies and technological innovations are constantly emerging, especially in the area of digital ecosystems and new technologies-particularly with regard to artificial intelligence, blockchain, and IoT. The definition of inclusion and exclusion criteria poses a further challenge. The criteria must be defined in such a way that they enable a comprehensive but selective analysis. Particularly in interdisciplinary research fields, it can be difficult to make a clear distinction between relevant and non-relevant literature. To ensure that only the most meaningful studies are considered, the search process must be iterative by further refining the criteria depending on the search results (Levy & Ellis, 2006). An additional difficulty arises from the qualitative differences between the existing studies. Many studies on digital ecosystems and their influence on crisis management or sustainability are based on case studies or conceptual models, while there are fewer comprehensive empirical studies. This makes comparability difficult and requires critical reflection on the methodological quality of each study. Unclear definitions or methodological inconsistencies could lead to different concepts being mistakenly equated, which could compromise the validity of the result (Snyder, 2019).

In addition to the general methodological concerns, specific challenges arise in connection with the theoretical model development of this work. One fundamental issue is scalability and industry transferability, as digital transformation is progressing at different speeds across industries. Technology-driven sectors lead the way, while others face technological and regulatory barriers (Ivanov & Dolgui, 2020). The framework must therefore consider sector-specific modifications. The model is essentially based on a concept developed through the analysis of extensive literature. However, it still needs to be tested in practice to prove its effectiveness (Eisenhardt & Graebner, 2007). While theoretical coherence is ensured, future research must test its practical applicability. Ethical issues such as bias in algorithms, data protection, and rules in digital systems also need to be considered, which complicates matters (Mittelstadt et al., 2016; Casino et al., 2019). To address these issues, the research adheres to established frameworks, carefully selects the literature (Snyder, 2019), and ensures relevance by incorporating industry perspectives (Torraco, 2016). The model is also designed to adapt to new technologies and regulations. Therefore empirical validation remains essential to refine and optimize its real-world applicability.

5. Literature synthesis and results: Thematic analysis

Building on the methodological foundations outlined previously, this section focusses on analyzing current research on how MNCs can integrate digital ecosystems to not only reduce the impact of global supply chains but also to promote sustainability goals and increase resilience. In other words, this report focusses on how companies can leverage technology not only to address immediate crises, but also to advance long-term sustainability goals and comply with evolving regulatory requirements. This is essential given that global supply chains are currently under unprecedented pressure due to increasing uncertainties, including geopolitical conflicts, the COVID-19 pandemic, and climate change. These events have shown weaknesses in supply chains and the importance of being resilient and adaptable. People are starting to see AI technologies as helpful tools for keeping an eye on things, predicting problems, and handling crises. But we haven't really focused enough on making sure they fit with sustainable goals and regulations. Current literature emphasizes either the integration of AI into crisis management or the incorporation of sustainable practices within supply chains. As an illustration, research has explored how AI can enhance supply chain resilience (Hu & Yao, 2023) and how technological innovations affect sustainable supply chain management

(Yu et al., 2022). However, few approaches effectively combine these two dimensions, even if this kind of synthesis is increasingly necessary in the light of regulatory requirements such as the EU Supply Chain Act. This thematic analysis is divided into four core areas, which together aim to provide a comprehensive foundation for developing a holistic model for integrating digital ecosystems and sustainability in supply chain crisis management. First, digital ecosystems and sustainability will be considered separately and then brought together later in this chapter in order to gains as many insights as possible.

5.1 Digital ecosystems in supply chain management

The increasing complexity and vulnerability of global supply chains has led to an increasing reliance on digital technologies to improve resilience and agility. The results of the McKinsey Global Supply Chain Leader Survey 2024, which highlights the importance of digital transformation in addressing supply chain vulnerabilities, support this assumption. In the survey it is mentioned that the rapid development of advanced digital tools is opening new possibilities in supply chain planning, operations, and risk management. It is suggested that AI systems might have the potential in the future to automate the analysis of multiple types of data sources from a variety of suppliers, logistic providers, shop floor data systems, and in-house demand-forecasting systems (Alicke & Foster, 2024). This results underscore the importance of modern technologies in building resilient supply chains. The concept of digital ecosystems represents a transformative change in supply chain management. These ecosystems go beyond traditional linear models and create dynamic, interconnected networks. By leveraging cutting-edge technologies such as the Internet of Things, artificial intelligence, blockchain and cloud computing, digital ecosystems improve the visibility, agility, and resilience of the entire supply chain. Companies are changing the way they deal with disruptions, making it easier for them to run smoothly in a world that's more unpredictable than ever (Culotta et al., 2022; Schallmo et al., 2024; Heinbach & Thomas, 2023). In the supply chain world, a digital ecosystem is essentially a network that encompasses customers, manufacturers, suppliers, and distributors, all connected by technology. Unlike traditional supply chains, which often operate in siloed spaces and involve a lot of manual labor, these digital ecosystems enable better communication and smarter decision-making (Bhawna et al.,2024; Winkelmann et al., 2024; Fornasiero & Tolio, 2024). With the advent of tools such as enterprise resource planning (ERP) software and barcodes, supply chains have evolved from manual processes to semi-automated systems. Recently, with advances in IoT, AI and blockchain, we've seen supply chains turn into fully digital systems. These technologies allow for predictive analytics, real-time monitoring, and better data management, which are key to tackling today's issues (Vijaykumar et al., 2024; Aditya et al., 2024; Tsolakis et al., 2023). Traditional supply chains operate on a linear trajectory: raw materials are delivered to manufacturers, who then distribute the finished products to wholesalers and retailers, before they reach consumers. This lacks flexibility and is susceptible to disturbances like inventory shortages or logistical delays. Conversely, digital ecosystems possess a high degree of adaptability and collaboration, allowing for real-time data sharing among companies throughout the supply chain facilitating proactive responses to potential problems (Katsaliaki, et al., 2022; Grover et al., 2024; Holzwarth et al., 2022).

5.1.1 Key technologies driving digital transformation

Digital ecosystems in supply chain management are changing the game by bringing in new tech that makes processes faster, clearer, and more responsive. This shift is mainly due to technologies like the Internet of Things, artificial intelligence, blockchain, cloud computing, digital twins, 5G, edge computing, and cybersecurity. Such ecosystems cover a wide range of disruptions and can be flexibly adapted to various crisis situations. Thanks to their real-time data analysis and precise predictive capabilities, these technologies are a valuable tool in corporate crisis management. AI-based systems make it possible to not only process historical data but also consider current market and operational data to identify potential disruptions early and initiate proactive measures (Belhadi et al., 2024). A prominent example of the use of AI in the supply chain is Blue Yonder’s software, which is based on predictive analytics and helps companies identify inventory problems early on. Walmart uses Blue Yonder to optimize its inventory levels and track demand trends in real time. This technology enables the company to identify anomalies and deviations from standard demand curves, thus avoiding inventory shortages or overstocking (Filipsson, 2025; Sodhi & Tang, 2021). With the help of Blue Yonder, Walmart was able to reduce its inventory costs and significantly increase supply chain efficiency, which is an improvement that is crucial in times of crisis (Sodhi & Tang, 2021). The platform uses sophisticated algorithms and machine learning techniques to analyze both historical and real-time data, enabling accurate predictions of future demand fluctuations. With this technology, companies can anticipate fluctuations in demand and thus avoid inventory shortages or surpluses. Resilinc is another platform that uses machine learning. This risk analysis platform uses ML algorithms to identify potential supply chain disruptions, particularly with regard to environmental and production risks. Resilinc collects data from various sources, including social media, news, weather forecasts, geopolitical developments, and economic reports, to identify and warn of emerging crises early on. Companies like Cisco and NVIDIA use Resilinc to keep an eye on their supply chains and deal with unexpected risks (Resilinc Solutions Pvt Ltd., 2025). The platform helps them identify potential problems before they impact production. AI and machine learning are particularly advantageous here because of their ability to adapt quickly. These self-learning algorithms analyze new data and improve their predictions over time. This allows them to adapt to market changes and the onset of disruptions (Choi et al., 2018).

The Internet of Things has become indispensable in crisis management. It helps companies track their supply chains in real time and identify potential problems immediately. By connecting physical devices and sensors, companies can continuously send and receive data, allowing them to closely monitor transport routes, inventory levels, and production processes. This real-time data provides a valuable basis for early detection of disruptions and helps increase the resilience of supply chains (Ahmed et al., 2021). A prominent example of the use of IoT in supply chain management is SAP IoT Supply Chain Management, a platform that enables companies to monitor their storage and transportation conditions in real time to quickly detect potential risks arising from environmental challenges such as natural disasters (SAP, 2021; Ahmed et al., 2021). SAP's IoT solutions help keep tabs on important factors like temperature, humidity, and pressure that matter for certain products and production processes. Siemens, for example, uses IoT sensors to monitor temperature-sensitive products and ensure their safe storage and transport (*SITRANS store IQ.*, n.d.; Zervoudakis et al., 2022). This real-time monitoring detects problems such as temperature fluctuations or improper storage before they lead to production issues. Zebra Technologies demonstrates how IoT can help in emergencies with its tracking solutions. These technologies provide companies with quick information about what is happening in the warehouse and enable large logistics companies like DHL to keep an eye on their inventory levels and delivery times. Zebra Technologies makes it possible to monitor the entire flow of goods from supplier to end consumer, significantly improving supply chain transparency and efficiency (Ruppik, 2023; DHL, 2020). This not only reduces the risk of warehouse shortages but also helps to identify and resolve delays in logistics at an early stage. The Internet of Things really helps supply chain management by collecting accurate data from the real world. This info can be used to make better decisions and spot risks early on (Ahmed, 2021). With tools like sensors and tracking tech, businesses can catch potential issues before they turn into bigger problems. These tools help automate and improve supply chain processes, allowing companies to react quickly when disruptions happen.

Lately, blockchain technology has gained importance in crisis management, particularly because of its ability to store transaction data transparently and immutably along the entire supply chain. With this technology, complete traceability is possible and it is guaranteed that every transaction from the producer to the end user is recorded in a way that cannot be altered. This transparency enables companies to not only quickly detect disruptions but also respond to potential risks in the supply chain before they lead to serious problems (Saberi et al., 2019). An outstanding example of the use of blockchain technology is IBM Food Trust, a platform specifically developed for the food industry. With IBM Food trust, companies can monitor food throughout the entire supply chain to ensure compliance with quality standards and respond quickly to food safety concerns. Walmart uses this platform to confirm the origin of food products and to detect potential hazards such as food contamination in a timely manner. By using blockchain, Walmart can respond to problems more quickly because all relevant information is available in real time and in a tamper proof manner (*Walmart's food safety solution using IBM Food Trust built on the IBM Blockchain Platform*, n.d.; Tian, 2016). This really cuts down the time it takes to find the sources of contamination or problems in the supply chain, which is important during crisis. Another good example is Trade lens, a blockchain platform create by Maersk to handle cargo documents and reduce risks in international trade. TradeLens enables clear and secure documentation of transactions and provides stakeholders with real-time access to data on the movement of goods. This transparency enables the immediate detection of delays, irregularities, or other disruptions in global trade, thus contributing to early identification and response to risks (Jensen et al., 2019). In particular, during periods of geopolitical tensions or global emergencies, blockchain has the potential to enhance the information flow and promote collaboration among parties. The great advantage of blockchain technology in crisis management is its high level of data security and traceability. The immutability of blockchain helps companies ensure that the data used for analysis and decision-making is accurate and immutable (Saberi et al., 2019). This is especially important in times of crisis when quick and precise decisions are required to reduce negative impacts on the supply chain. In addition, the transparency of the system strengthens trust between actors and ensures that information is shared faster and more efficiently.

Digital twins have become increasingly important in crisis management in recent years, especially because they can generate virtual representation of real-world systems. With these digital twins, companies can monitor their supply chains in real time, identify potential disruptions early, and take proactive action. By modeling different situations, they can investigate the impact of disruptions and develop appropriate responses (World Economic Forum, 2024). The application at Walmart is a prime example of the use of digital twins. To improve the customer experience and optimize store design, the company uses digital twins. By simulating different layouts in a virtual environment, Walmart can make informed decisions before physical damage occurs. This approach is already being used in more than 1700 stores, helping boost sales and streamline operations (The Sun, 2024). Digital twins help supply chain companies remain agile and responsive. They provide real-time insights into areas such as inventory and shipping. This allows companies to identify and address issues immediately, which is especially important during challenging times (World Economic Forum, 2024). Digital twins thus offer the opportunity to proactively monitor and manage supply chains. By running and analyzing different scenarios, they can spot potential problems early and implement appropriate countermeasures. This ability is essential during a crisis to reduce delays and keep the supply chain running.

Cloud computing, edge computing, and 5G have recently become key factors in crisis management, primarily because of their ability to process and analyze data instantly. These technologies help companies identify and respond more quickly along their supply chains, enabling them to identify and address risks early on. Cloud computing offers the ability to centrally store and process vast amounts of data, giving companies a clear overview of their supply chains. By using cloud solutions, companies can collect and analyze data to make informed decisions and act quickly when problems arise. Accenture points out that cloud providers play an important role in addressing supply chain issues and achieving sustainability goals by sharing data with skilled professionals (*Cloud Services | Accenture*., n.d.; Ignjatović et al.,2024). Edge computing complements cloud computing by moving data processing closer to where the data is generated. This reduces latency and enables faster data analysis, which is particularly beneficial in time-critical situations. IBM offers edge solutions that help clients deliver rich digital experiences and increase operational efficiency in areas such as Industry 4.0, supply chain, and asset management (Carvalho et al., 2021; Appius et al., 2021; Liu et al., 2022c). The introduction of 5G improves connectivity and enables seamless integration of edge and cloud computing solutions. With higher bandwidth and lower latency, companies can access data in real time, increasing the visibility and efficiency of their supply chains. According to an article by GEP, edge computing and 5G provide the computing power, performance, and reliability to support warehouse automation and automated material handling, including asset tracking and tracing to eliminate data blind spots in the supply chain (GEP, 2023). The partnership between T-Mobile and NVIDIA to develop AI-RAN (Artificial Intelligence with Radio Access Networks) is a prime example of the use of these technologies. This network optimization solution combines artificial intelligence with advanced connectivity to increase network efficiency and responsiveness (Pillay, 2024). By using cloud computing, edge computing and 5G, companies can make their supply chain more resilient and adaptable. These technologies help gather and analyze data in real-time, which can spot problems early and allow companies to take actions right away. This kind of capability is super helpful when things go wrong, helping to keep the supply chain running.

Big data analytics has become essential for managing supply chain issues. It enables the processing of large and diverse data sets and enables companies to identify potential problems in its initial stages. Companies can identify trends based on various information's such as production statistics, weather reports, political news, or market analyses. These insights act as early warning signals (Choi et al.,2018). This analytical capability makes big data an indispensable tool for strengthening supply chain resilience in a dynamic and often unpredictable world. Tableau, a business intelligence platform developed by Salesforce, is a prime example of big data analytics. It enables companies to visually represent supply chain data and identify trends that would otherwise be missed. Companies like Unilever use Tableau to improve their inventory planning. By merging historical with real-time data, they aim to improve future demand and forecasts and spot possible bottlenecks. Through this data visualization, Unilever is able to respond more rapidly to market changes and circumvent supply chain bottlenecks (*Data tells consumer stories at Unilever*, n.d). Another instance of pinpointing political conflicts and geopolitical risks is Kinaxis RapidResponse, a software solution that facilitates real-time supply chain analytics and planning. Companies like Ford have implemented Kinaxis to predict production outages and bottlenecks by merging and analyzing data from a variety of sources. Kinaxis provides a platform that enables Ford to respond quickly to fluctuations in demand or delivery delays, minimizing potential production disruptions (Trevor, 2017; Choi et al., 2020). The platforms enable the early detection of risks and the development of counter-strategies through the analysis of a comprehensive database that includes political events and market developments. In uncertain times, such as political conflicts or natural disasters, the ability to monitor and plan supply chains in real time is crucial. Big data analytics has some real benefits when it comes to looking at and understanding large amounts of data. It's pretty handy for dealing with different kinds of issues, like market changes, natural disasters, or delays in suppliers (Kouvelis et al., 2019). By combining historical data with real-time information and intelligent forecasts, companies can identify risks early and better manage their supply chains to address any issues that may arise. Leveraging big data for risk detection helps companies identify problems before they escalate and provides them with the information they need to make informed decisions in times of crisis. Combining different data types enables the creation of informed forecasts, which are essential for identifying and mitigating risks from global events. Everstream Analytics is an example of a highly flexible technology. This platform integrates data from various sources, including weather forecasts, political events, and logistics issues, providing a comprehensive solution for identifying and analyzing supply chain risks. Everstream Analytics enables companies to respond quickly to a wide range of disruptions by providing a complete picture of potential risks in their supply chains (Everstream AI, 2025; Kouvelis et al, 2019). The true power of this technology lies in its ability to handle many disruptions and help companies develop intelligent problem prevention plans. The variability and flexibility of modern technologies are therefore crucial to meet the different demands and disruptions in a complex, globalized supply chain landscape. By integrating and leveraging these technologies, companies can increase their resilience and respond efficiently to a wide range of risks.The interplay of these technologies has the ability to fundamentally transform supply chain management, since it creates a dynamic and adaptive system that significantly increases efficiency, transparency, and responsiveness.

5.1.2 Benefits and challenges of implementation

As mentioned above, building a digital ecosystem offers comprehensive benefits for crisis management in supply chains. In the face of increasing market volatility, geopolitical uncertainties, and climate-related disruptions, the importance of digital solutions for companies seeking to improve their resilience, agility, and transparency is growing (Ivanov & Dolgui, 2020). According to Köhler et al. (2021b), such ecosystems enable the smooth integration of various actors, technologies, and data sources, enhancing the efficiency of supply chains and their resilience against external shocks. An important advantage of digital ecosystems is their capability to identify supply chain disruptions at an early stage. When real-time data and sophisticated analytical tools are combined, it becomes possible to detect potential disruptions at an early stage and to introduce preventive actions (Xu et al., 2021). With the help of predictive analytics and machine learning models, companies can foresee significant risks and react to them instantaneously (Choi et al., 2018). A particularly innovative approach to early detection of disruptions is the implementation of cognitive digital twins (CDT). These use AI-powered simulations to evaluate potential supply chain scenarios and generate recommendations for action in real time (Ashraf et al., 2024). As noted by Ashraf et al. (2024), CDTs provide substantial advantages by allowing decision-makers to address disruptions prior to their escalation. This holds especially true for global supply chains characterized by intricate interdependencies, where delays in one link in the chain can have far-reaching effects on the entire value chain. As Hu (2024) notes, digital ecosystems improve the resilience of supply chains through the use of intelligent recommendation systems, which serve as the first line of defense against disruptions. These systems examine large amounts of data to help companies make informed decisions and improve their responsiveness (Sarkis, 2020). Hu (2024) argues that data-driven recommendation systems help identify risks and uncover alternative supply strategies. For example, if a primary source fails, they can immediately suggest other suppliers or identify alternative transportation routes for good to reduce delays. The system can continuously learn from past disruptions and develop optimized strategies for future events by leveraging reinforcement learning and adaptive algorithms (Ivanov & Dolgui, 2020). The integration of blockchain technology into digital ecosystems offers further benefits in terms of data integrity, traceability, and security (Liu et al., 2022b; Liu et al., 2022a). Blockchain can make the storage and exchange of supply chain data tamper-proof, leading to improved process transparency and traceability (Saberi et al., 2019). Liu et al. (2022b) describes that optimizing data management in supply chains can be achieved through the integration of blockchain technology and digital twins. Decentralized storage and tamper-proof documentation of transactions not only increases the trustworthiness of supply chains but also reduces the risk of data manipulation and fraud. Blockchain can, for example, be used for the seamless documentation of sustainability certificates or the tracking of goods in real time, enabling companies to better comply with regulatory requirements (Köhler et al., 2020).

Blockchain technology boosts cybersecurity in supply chains by making sure that only the right people can see important information. This matters a lot since supply chains are more at risk of cyberattacks these days, which can disrupt business and put private data at risk (Ivanov & Dolgui, 2020). Digital ecosystems also increase companies' agility and their ability to respond to market dynamics. By using AI-supported decision models and connected data platforms, companies can respond more quickly to shifts in demand, production bottlenecks, or unforeseen disruptions (Choi et al., 2018). Saberi et al. (2019) argue that digital ecosystems provide companies with the means to create adaptive strategies that can be adjusted flexibly to suit various scenarios. A data-driven supply chain network, for instance, can implement dynamic inventory and warehousing strategies to prevent delivery bottlenecks or optimize transportation needs based on current conditions (Ivanov & Dolgui, 2020). Even with the potential of these technologies, companies run into some real challenges when trying to put them to use. One big issue is the quality of the data, which is super important for making good decisions (Cho & Lee, 2021). Companies often find it difficult to bring together different data sources and ensure that everything is consistent and reliable. A common problem is that data from different sources can be very heterogeneous. In supply chains, there are a variety of actors and processes, each using their own formats and systems. Companies need to ensure that the data they collect is compatible to perform accurate analytics. This is difficult, especially when the data comes from different companies that may have their own methods of collecting and processing information (Sodhi & Tang, 2021). One example is the implementation of IoT sensors, which can generate different data formats depending on the region or company. These discrepancies can complicate the integration of IoT data by hindering the linking and analysis of information from different sources. Another problem is the lack of uniform data standards in global supply chains. As supply chains become more international, it is important that companies have access to the same data standards worldwide to ensure consistent and comparable analysis of the data (Kouvelis et al., 2019). Without a standard way of doing things or clear communication, it can be tough for companies to pull together important data from various sources. This often leads to errors and delays that can significantly impact a company's ability to address supply chain issues. Another key factor in deploying new technologies is data quality. If data is incomplete, inaccurate, or outdated, it can cause problems and inadequate crisis response. Companies must therefore find ways to ensure their data is accurate, up-to-date, and complete. Technologies like predictive analytics or real-time monitoring don't work with poor data quality (Kankam et al., 2023). This particularly represents a rapid response to unforeseen events such as natural disasters or geopolitical tensions, where both accurate and timely information is essential. One example of the difficulties regarding data quality and integration are the different formats of IoT data. IoT sensors deployed in different sectors or organizations may use different formats for data storage and transmission. Due to these differences, merging data from different sources can be challenging. This limits the use of IoT data for supply chain risk monitoring and analysis. To address these challenges, companies need better ways to combine data that can handle different formats and keep everything consistent. Problems with data quality can really hold back the use of new technology in supply chain crisis management. To make the most of these technologies, businesses need to have the right systems and processes ready to gather, handle, and check high-quality data.

Along with the difficulties regarding data quality and integrity, the technological infrastructure requirements also represent a significant obstacle to the adoption of modern technologies in crisis management. In particular, the high investment costs for implementing IoT and AI technologies as well as the infrastructural deficits in certain regions make the use of these technologies in global supply chains difficult (Sodhi & Tang, 2021). However, the required technological infrastructure is a prerequisite for the successful use of IoT and AI-based solutions that enable precise and timely analysis of supply chain risks. The implementation of IoT and AI technologies requires significant investments in hardware, software, and the associated IT infrastructure. Systems based on IoT that utilize sensors to oversee inventory, production processes, and transport conditions, along with AI solutions, for disruption analysis and forecasting, necessitate not just the procurement and integration of devices and systems but also employee trainings and adjustment to current IT architectures. The significant investment costs represent a serious obstacle, especially for SMEs or companies located in resource-poor areas (Ardito et al., 2024; Roux et al., 2023). Research shows that companies with financial constraints struggle to build the necessary infrastructure to integrate and utilize modern technologies into their supply chains (Baryannis et al., 2019). The costs of operating and maintaining these technologies can add up, making it difficult for companies to determine the return on their investments. Another major challenge with adopting modern technologies is that many developing countries lack the necessary internet or cloud services. For example, using IoT and AI can be very difficult in places without stable and fast internet access. These IoT sensors and data systems require a good internet connection to send and analyze data instantly. Therefore, in regions with weak internet infrastructure, these technologies are difficult to implement (Baryannis et al., 2019). In addition, cloud infrastructure also plays a central role in storing and analyzing the collected data. In developing countries, where access to cloud services and associated computing capacity is limited, the use of cloud-based AI platforms and big data analytics is significantly limited. The infrastructural deficiencies in certain regions can prevent companies from monitoring their supply chains in real time and making quick decisions in case of disruptions. Companies that rely on implementing IoT and AI technologies therefore often have to make additional investments in the required infrastructure or develop alternative solutions to respond to these challenges (Tsolakis et al., 2023). Some companies try to overcome these challenges by resorting to hybrid solutions that use a combination of on-premises and cloud-based data processing models. These can serve as a pragmatic solution in certain situations to minimize the impact of inadequate infrastructure. This suggests that technological infrastructure is one of the biggest challenges in implementing modern technologies in crisis management, both from a financial and infrastructure perspective. Companies must be prepared to make significant investments and deal with local conditions in order to successfully integrate IoT and AI technologies.

Cybersecurity and data protection are crucial when it comes to implementing modern technologies for crisis management in supply chains. With the increasing interconnectedness of systems and the processing of large amounts of sensitive data, data leaks and cyberattacks pose a significant threat and force companies to implement high security standards (Hosseini et al., 2021) Particularly critical are the risks associated with the use of IoT sensors and blockchain technologies, which constantly exchange and store data, creating potential points of attack for cybercriminals (Tian et al., 2023). IoT devices in supply chains that are responsible for real-time monitoring and automation of processes are particularly vulnerable to cyberattacks. These devices are frequently insufficient secured, presenting potential vulnerabilities for malicious actors. Since IoT devices collect large amounts of operational data and often transmit it to central systems in real time they can serve as a gateway for cyberattacks that can lead to data loss, system failures or even tampering, if they are inadequately protected (Zhang et al., 2021). To counteract this issue, companies need to have solid security measures in place, like encrypting the data they gather and regularly updating their devices to prevent attacks (Tian et al., 2023). Another major concern with today’s technology is compliance with data protection laws such as the GDPR in the EU (Wolford, 2023). This laws sets strict rules for the collection, storage, and use of personal data. However, many modern technologies, particularly IoT and blockchain, can make meeting these requirements difficult. For example, IoT devices used to monitor supply chains could collect personal data without adequately protecting people’s privacy. Similarly, businesses that utilize blockchain technologies need to guarantee that the stored transaction data adheres to GDPR regulations, since this data often includes personal information (Wolford, 2023; Fabiano, 2017; Perera et al., 2020). One particular challenge is the potential for conflicts between data security requirements and data protection guidelines. Blockchain technologies, for example, which are often used as an immutable database for transactions and supply chain information, collide with the principle of the right to be forgotten written down in the GDPR (Wolford, 2023).

Permanently storing data on the blockchain could make it difficult to delete data later, which in turn could violate the GDPR's legal requirements (Fabiano, 2017; Narayanan et al., 2021). Companies that rely on these technologies must therefore take additional precautions to ensure compliance with data protection regulations without compromising the security of the data. Companies must ensure that their IoT devices and blockchain solutions are GDPR compliant by implementing appropriate security measures and promoting data transparency. This requires close cooperation with data protection officers and continuous review of security measures. An example of companies that are intensively addressing these challenges is IBM's collaboration with the Food Trust Blockchain, which aims to ensure transparency and traceability in the food supply chain while adhering to data privacy regulations (*Walmart's food safety solution using IBM Food Trust built on the IBM Blockchain Platform*, n.d.; Perera et al., 2020). IoT-based solutions such as SAP IoT Supply Chain Management have integrated security mechanisms to ensure compliance with data protection regulations. In general, compliance with cybersecurity and data protection is a major challenge when using modern technologies in crisis management. To maintain stakeholder trust and avoid legal consequences, organizations must ensure that their technological implementations are both secure and legal.

Another decisive factor for the use of modern technologies in crisis management is acceptance by people and the lack of qualified personnel. When introducing modern technologies, especially highly complex technologies such as AI and blockchain, they are often met with resistance from employees and managers. This is because such changes require an adaptation of current working methods and thought processes. Studies indicate that change in organizations can cause metal blocks among employees as they worry about how the changes will affect their jobs. Managers can also be reluctant to adopt new technologies, especially if the benefits are not immediately apparent and the initial cost of setting up new systems can be high (Sia et al., 2016). A crucial factor for resistance to the introduction of modern technologies is trust in these new systems. Many employees, particularly in relation to AI-based solutions and blockchain technologies, are uncertain about the impact of these technologies on their daily work, which can result in fears of job loss or feeling of surveillance. Thus, in order to reduce resistance to change, companies should take into account both the technical and social dimensions when implementing such technologies (Scheuer, 2020; Eib, 2023). Management may also show reluctance to adopt new technologies, particularly when the ROI is not yet evident and implementing complex systems necessitate significant upfront costs (Sia et al., 2016). In order to promote the acceptance of new technologies, it is essential to have a change management process that is well-organized, involves employees in the change process, and communicates transparently (Golgeci et al., 2025; Tursunbayeva, 2024). This can be illustrated using the example of the introduction of AI-based systems in the logistics sector. In this context, training and education initiatives are offered to equip employees with the necessary knowledge and to deal with their concerns (Davenport, 2018). In addition to the acceptance of change, the lack of qualified personnel poses a considerable difficulty. Advanced technologies such as AI and blockchain require specialized knowledge that is both difficult to find and costly to develop. Many organizations face the challenge of finding highly skilled professionals who are able to oversee and execute these technologies efficiently. The skills shortage in the areas of data science and AI is particularly pronounced, as the demand for skilled labor is constantly increasing worldwide while the supply cannot keep pace (Barenkamp, 2024; Hüsch et al., 2023). Companies must therefore invest in the training and further education of their employees in order to keep pace with technological developments. This includes working with universities and educational institutions to ensure that the next generation of skilled workers is adequately prepared for the demands of the industry (Gärtner & Gärtner, 2020). Meaning human acceptance and skills shortages are key challenges in implementing AI and blockchain technologies in crisis management. Companies therefore need to drive not only technological, but also cultural and organizational change to overcome resistance to change and ensure that sufficient skilled professionals are available to use the technologies successfully.

Sustainability could greatly facilitate the integration of new technologies into digital ecosystems by providing a clear framework of goals and priorities. It could serve as a guideline that directs technological investments into areas that are not only more efficient, but also more environmentally and socially responsible.

5.2 Sustainability as a multifaced approach to supply chain resilience

Supply chain resilience has become a key challenge of the modern economy. After all, sustainability is highly valued in society and politics today because it offers answers to the most pressing challenges of our time. Society is becoming increasingly aware of the finite nature of natural resources and the effects of climate change (Scholten & Stevenson, 2024). From a political perspective, sustainability is viewed as essential for enduring stability and prosperity. Governments globally are establishing ambitious emission reduction targets, aimed at safeguarding biodiversity and advancing a circular economy. Companies are held accountable through the enactment of laws and regulations like the Supply Chain Duty of Care Act or ESG criteria. Sustainability is also seen as a driver of innovation. Companies that focus on sustainability at an early stage secure competitive advantages and contribute to shaping a sustainable economy (*BMAS - Supply Chain Act*, n.d.; World Economic Forum, 2024). This is illustrated by the example of Maersk, which is investing in more sustainable freight transport and communicating this commitment to the outside world (Maersk, 2024). Sustainability therefore provides a standardized framework that helps companies to overcome immediate crises and develop long-term resilience. Elkington (1997) argues that the triple bottom line approach, which encompasses environmental, social, and economic objectives, is essential for enhancing supply chain resilience and ensuring that companies achieve short-term success while also developing stable and responsible business models in the long term. The basis of this approach is the linking of ecological, social, and economic dimension, which are analyzed in detail in the following chapters. Chapter 5.2.1 Environmental management and crisis prevention explains how sustainable environmental strategies can help to minimize risks and respond proactively to environmental changes, such as disruptions caused by climate change (Sodhi & Tang, 2021). Careful planning and management of environmental resources plays a key role in maintaining the integrity and stability of supply chains and securing them for the future. 5.2.2 Social Sustainability: Stakeholder Engagement and Ethical Practices examines how corporate social responsibility influences corporate resilience. It encompasses fostering trust and setting up ethical business norms by working together with different stakeholders. Not only does social sustainability foster society's long-term well-being, but it also strengthens the reputation and stability of supply chains, as a stable social context guarantees a smooth business environment (Lamming & Hampson, 2019). Finally, 5.2.3 Economic sustainability: long-term viability and risk mitigation analyses how companies can secure their economic stability in the long term in order to not only be separated short-term crises, but also to maintain their competitiveness in the long term. The focus here is primarily on risk management, investment in innovation and diversification of suppliers in order to strengthen resilience to future market and production disruptions (Wieland & Wallenburg, 2012). Overall, the triple bottom line approach makes it clear that supply chain resilience can only be achieved by taking an integrated view of the environmental, social, and economic dimension. Companies that harmonize these three aspects are not only able to survive crises, but are also better prepared for long-term challenges (Gimenez & Tachizawa, 2012).

5.2.1 Environmental management and crisis prevention

The integration of environmental management into supply chains is a key aspect of the triple bottom line approach, which aims to combine environmental, social, and economic objectives. Not only does effective environmental management contribute to safeguarding the environment, it also improves supply chain resilience against potential crises. Companies can reduce risks and enhance their adaptability to unforeseen circumstances by implementing proactive environmental strategies. To manage the environment effectively, it is crucial to apply sustainable practices throughout all stages of the supply chain. This encompasses cutting emissions, optimizing resource use, and reducing waste to the greatest extent possible. Such measures contribute to environmental protection and can also lead to increased operational efficiency and cost reductions. They foster adherence to regulations and enhance the corporate image, thereby reinforcing connections with stakeholders (Svensson et al., 2018). Managing risk and spotting environmental issues are key to prevent big problems down the line. By looking at weaknesses in the supply chain, businesses can come up with smart plans to lessen the effects of environmental disruptions. For example, having suppliers from different areas can help ease the risk of supply shortages due to natural disasters (Ferdous et al., 2025). Close co-operation with suppliers and partners is also important for the implementation of environmental management strategies. By jointly working together and implementing sustainable practices, synergies can be used to achieve environmental optimization throughout the supply chain. A collaborative strategy makes it easier to share knowledge and adapt to environmental issues (Leite & Bengtson, 2018; Leite, 2022; Leite & Ingstrup, 2022). Including environmental management in the supply chain not only supports sustainability, but also strengthens crisis resilience. Companies that take proactive steps to manage environmental risks and adopt sustainable practices tend to be better equipped to handle unexpected events and succeed in the long term.

5.2.2 Social sustainability: Stakeholder engagement and ethical practices

Social sustainability is necessary for supply chain resilience within the framework of the triple bottom line approach, which brings together environmental, social, ad economic objectives. A key aspect is the commitment of stakeholders and the adoption of ethical business practices. Companies can assume social responsibility and create long-term stability and trust in their supply chains by taking into account the interests of all stakeholders and complying with ethical standards. The term stakeholder engagement implies the organized involvement of all relevant stakeholders in business activities and decision-making processes. These stakeholders encompass suppliers, customers, employees, investors, NGOs, and the communities where the company operates. By managing stakeholders proactively, companies can detect potential social risks early on and collaborate on solutions. According to Fritz et al. (2018), for decision-making and policymaking to be responsible, it is essential to identify and involve stakeholders throughout the supply chain. Building partnerships and having open conversations can help companies gain trust and reduce conflicts in society. Ethical business practices means respecting human rights, ensuring fair working conditions, being transparent, and acting with integrity. Implementing such practices can boost the company’s reputation and promotes long-term business relationships, while supporting social justice. Dmytriyev, Freeman and Hörisch (2021) point out the difference between traditional stakeholder management and a rights-based approach to corporate social responsibility. They suggest that companies should go beyond simply considering the interests of stakeholders, but actively protect the rights of those affected. This includes ensuring fair pay, a safe working environment and the prevention of exploitation throughout the supply chain. A comprehensive strategy is needed to integrate stakeholder engagement and ethical practices into the supply chain. Companies should focus on clear communication, regular audits, and training programs for suppliers and employees. In addition, developing codes of conduct and setting clear ethical standards is essential. Svensson et al. (2018) emphasize that the direct and mediated impacts between economic, social, and environmental elements must be considered within the triple bottom line approach to successfully implement sustainable business practices. By consistently applying stakeholder engagement and ethical practices, companies can fulfil their social responsibility and increase the resilience and sustainability of their supply chains. This leads to an improved risk management approach, greater stakeholder trust and sustainable business success.

5.2.3 Economic sustainability: long-term viability and risk mitigation

Economic sustainability, a fundamental component of the Triple Bottom Line framework, emphasizes the importance of sustained profitability in supply chains and the implementation of effective risk management strategies. Companies aim to make money in the long run while also being good to the planet and the community. To do this, they need to focus on sustainable practices that allow them to balance quick profits with lasting stability. This means putting money into smart technologies that use resources wisely, streamlining operations, and encouraging new ideas to stay ahead in a changing market. For example, incorporating circular economy principles such as recycling, reuse, and remanufacturing can lead to cost savings and new revenue streams, thus improving economic resilience (Aguiñaga et al., 2018). To maintain economic performance despite uncertainty, effective risk mitigation is critical. This involves identifying potential threats, including supply chain disruptions, fluctuations in market conditions, and changes in regulations, and implementing tactics to proactively address them. Collaborating with suppliers to improve sustainability practices can mitigate risks relegated to resource scarcity and regulatory compliance, thus improving the economic aspects of TBL (Nogueira et al., 2025; Rashidi et al., 2020). To bring economic sustainability into the TBL framework, it is important to take a well-rounded approach that connects financial goals with caring for the environment and being socially responsible. This helps companies balance between their financial performance and sustainability efforts. For example, working with sustainable suppliers can boost all three areas of TBL, leading to better economic results along with environmental and social benefits (Nogueira et al., 2025; Rashidi et al., 2020). For businesses looking to thrive today, it’s important to focus on economic sustainability by aiming for long-term profits and managing risks. Companies can achieve lasting success and be more resilient by linking their financial goals with environmental and social concerns. In reality, many businesses tend to focus mainly on economic factors, while overlooking the environmental and social sides. This is where digital ecosystems can provide decisive advantages. Better data collection, analysis and transparency can help companies achieve multiple sustainability goals simultaneously (Ahmed et al., 2021; Saberi et al., 2019). These technologies help create a clearer picture of what sustainability looks like.

5.3 Integration of digital ecosystems and sustainability for enhanced resilience

There is a growing acknowledgment that aligning digital ecosystems with sustainability efforts represents an essential approach to enhancing organizational resilience. This is especially true in the context of the Triple Bottom Line (TBL) framework, which focuses on economic, and social performance. By leveraging digital technologies, organizations should be able to create synergies that strengthen their ability to withstand and adapt to disruption while promoting sustainable development. Digital ecosystems are made up of different technologies and platforms that allow easy sharing of information and teamwork among various people. To make these ecosystems more sustainable, we need to include social and environmental factors in our digital setups and methods. This helps companies keep track of their sustainability efforts better and make smarter decisions. As an illustration, the implementation of digital product passports, mandated by the European Union's Ecodesign Regulation for sustainable products, enhances supply chain transparency and aids circular economy practices by offering detailed insights into product materials and lifecycle effects (Roberts-Islam, 2024). To strengthen corporate resilience, the use of advanced digital technologies such as artificial intelligence (AI), resource management enabled by these technologies are essential for responding to unforeseen disruptions. A study by Quing and Jin (2023) shows that using AI in digital transformation helps companies become more sustainable. It aids in spotting social issues and avoiding environmental problems, which boosts their overall strength and works towards triple bottom line goals. When companies add digital tools to their sustainability efforts, they can enjoy several advantages that fit well within the triple bottom line framework. Economically, businesses can cut costs by becoming more efficient and finding new income streams through eco-friendly products and services. Digital technologies also help use resources better and reduce waste, which is good for the environment. Digital technologies also help use resources better and reduce waste, which is good for the environment. Plus, being transparent and involving stakeholders builds social trust and supports ethical practices. According to Stütz et al. (2023), a digital procurement workspace that prioritizes information integration, automation, analytics, and sustainability can significantly improve supply network management and underscores the connection between digital innovation and sustainable practices. While integrating digital ecosystems into sustainability goals offers significant benefits, companies must overcome hurdles such as data protection concerns, technological compatibility, and the need for significant investments in digital infrastructure. Bringing digital transformation and sustainability together means you need a smart strategy. It's important to consider potential downsides and ensure that new technologies don't exacerbate environmental or social problems. Linking digital systems with sustainability efforts can be a good step for companies seeking to thrive in today's changing world. This combined approach helps companies align their economic, environmental, and social goals, fostering sustainable success while supporting overall sustainability efforts.

5.3.1 AI and IoT for proactive management and sustainability strategies

By incorporating Artificial Intelligence (AI) and the Internet of Things (IoT) into digital ecosystems, we can transform proactive risk management and sustainability efforts in alignment with the Triple Bottom Line (TBL) framework, which includes economic, environmental, and social dimensions. AI and IoT technologies enable organizations to anticipate and mitigate risks by providing real-time data collection and advanced analytics. For example, in IoT ecosystems, AI-driven frameworks can improve cybersecurity by proactively identifying and addressing potential threats, thus securing operational integrity and economic performance (Bolanos, 2023). Thanks to AI's ability to examine large-scale data sets, risks related to environmental impacts, supply chain disruptions, and regulatory compliance can be identified early, enabling rapid intervention (Khalid et al., 2024). The fusion of AI and IoT contributes significantly to sustainability by improving resource utilization and minimizing environmental impact. The concept of a sustainable AIoT (Artificial Intelligence of Things) underscores the importance of strengthening the profit, human, and the planet aspects of TBL through the integrated use of AI and IoT, although this endeavor is fraught with complexities and tensions (Alaba et al., 2024). Bringing AI and IoT into corporate social responsibility plans can help manage financial risks and support sustainable growth. It's really important to have good policies in place for using these technologies safely and consistently (Kumar et al., 2024). While AI and IoT can bring some great advantages, we need to keep a close eye on how they're used to make sure they don't harm sustainability. For example, the energy consumption associated with AI and IoT activities can lead to environmental damage if inadequately managed. Companies should therefore develop strategies to mitigate these impacts, for example, by adopting energy-efficient technologies and methods (Alaba et al., 2024). This suggests that the strategic integration of AI and IoT into digital ecosystems serves as a catalyst for proactive risk management and sustainability insights, thus enhancing the TBL framework.

By leveraging these technologies, companies can strengthen their resilience and contribute to the achievement of sustainable development goals.

5.3.2 Blockchain and cloud computing to promote transparency and collaboration

The integration of blockchain technology and cloud computing into digital ecosystems offers significant opportunities to improve transparency and collaboration and is consistent with the triple-bottom-line approach that considers economic, environmental, and social factors. Blockchain technology can create immutable and traceable records, increasing transparency across various sectors. By implementing blockchain, companies can improve the traceability of their products and services, thus building stakeholder trust. Ksheri (2021) emphasizes that blockchain technology, which provides tamper-proof records, can enhance transparency and citizen trust. The flexible and scalable infrastructure of cloud computing enables real-time access to applications and data. This technology promotes collaboration among different participants through shared access to resources and information. Integrating blockchain technology into cloud computing can increase the efficiency and security of data management systems, thus optimizing business processes. Liu et al.(2022a) discuss how blockchain, in combination with cloud computing, can promote transparent data markets by enabling fair and consortium-based management. The synergy of blockchain and cloud computing can have a positive impact on all three dimensions of TBL. Companies can lower costs and improve efficiency by enhancing data integrity and security. Transparent supply chains facilitate improved oversight of environmental standards and foster sustainable practices. Heightened transparency strengthens consumer trust and promotes ethical business practices. In general, the incorporation of blockchain technology and cloud computing into digital ecosystems presents a promising strategy for fostering transparency and collaboration that aligns with the objectives of the Triple Bottom Line.

5.3.3 Digital twins and big data analytics: simulations, optimization, and prevention

Digital twins (DT) and big data analytics are recognized as transformative technologies in supply chain management, especially in simulation, optimization, and proactive disruption management. According to Ivanov et al. (2019), a digital twin is a virtual model of a physical system that employs real-time data to simulate and examine the system's behavior and performance. Through the incorporation of big data analytics, organizations can handle massive datasets and acquire valuable insights that enhance decision-making and efficiency. Thanks to their ability to simulate various scenarios, digital twins enable companies to anticipate potential supply chain disruptions and develop appropriate countermeasures. By combining simulation and optimization, companies can evaluate and adapt their supply chain strategies to increase resilience and reduce risks (Ivanov et al., 2019). For example, companies can use digital twins to identify bottlenecks and evaluate different routes or suppliers to mitigate the impact of disruption. Digital twins enable proactive disruptions management through real-time data monitoring and analysis. Firms are able to address irregularities at an early stage and implement preventative measures prior to the onset of significant disturbances (Tao et al.,2019). This results in greater agility and flexibility within the supply chain, enabling companies to respond more effectively to unexpected occurrences. Digital twins have been implemented at a global original equipment manufacturer (OEM), resulting in an 8% reduction in freight and damage costs through optimized transport management strategies (Oca et al., 2024). Another example is the development of a cognitive digital supply chain that uses deep learning techniques to detect disruptions early on and increase the resilience of the supply chain (Choi et al., 2018). The integration of digital twins and big data analytics is transforming supply chain management by permitting businesses to improve their processes through simulation, optimization, and proactive disruption management. By leveraging these technologies, companies can not only increase efficiency but also increase the resilience of their supply chains to future challenges.

5.3.4 Balance between economic feasibility and sustainability

Integrating sustainability into digital systems using the triple bottom line model, which considers economic, environmental, and social aspects, can create opportunities for teamwork but also bring with it difficult decisions. The use of advanced technologies such as big data, blockchain, AI, and the Internet of Things can help balance these sustainability aspects and make things clearer and more efficient. Zimmer and Järveläinen (2022) pointed out that companies that implement sustainability-oriented changes can develop new ideas that increase profits while helping the planet and people. By embracing digital ecosystems, companies can use resources more efficiently, keep better track of their sustainability efforts, and create solutions that balance making money with being responsible towards the environment and society. Traditional approaches to sustainability often involves difficult decisions, but digital ecosystems can help companies better align their goals of profit, environmental protection and social responsibility. Investing in eco-friendly technologies like renewable energy can be pricey and might hurt a company’s short-term profits. Still, digital systems supported by AI and blockchain can help companies allocate resources better and cut down on waste, which can lower operating costs and promote environmental sustainability. For instance, using AI to analyze data can help factories use energy more efficiently by adjusting their energy use in real-time, leading to fewer CO_2 emission and saving money (Birsan, 2024).

According to Saberi et al. (2019), blockchain technology provides transparency in supply chains, counteracts greenwashing, and enables companies to demonstrate compliance with sustainability laws without incurring high audit costs. Fair compensation, ethical labor practices, and social investments often mean higher costs, which can reduce short-term profits. However, digital platforms can alleviate these problems by better managing employees, automating tasks, and sorting work more effectively. AI systems can optimize working hours to reduce stress and keep productivity high (Miemczyk & Luzzini, 2018). Digital financial tools, like smart contracts using blockchain, can ensure suppliers in developing nations get paid fairly and on time, thus reducing social inequality within global supply chains (Shou et al., 2019). Stricter environmental regulations can make products more expensive, thus affecting affordability and social equity. Digital systems can help by enabling circular economy models. IoT tracking improves product life cycle management and recycling, reducing waste while keeping costs under control (Hendiani et al., 2020). Furthermore, AI-driven logistics optimization can reduce emissions without increasing consumer prices by identifying the most efficient transportation routes and reducing fuel consumptions (Nair et al., 2021).

Although digital ecosystems can manage many sustainability trade-offs, some conflicts are still unavoidable. A significant hurdle is the substantial initial financial investment required to adopt AI, IoT, and blockchain technologies. Although these digital solutions provide long-term cost savings and sustainability advantages, their implementation necessitates considerable financial resources, which can be especially challenging for small and medium-sized enterprises (SMEs) (Zimmer & Järveläinen, 2022). While AI-powered automation and decision-making can increase efficiency and reduce costs, they can also lead to job displacement. The substitution of human labor with automated systems can negatively impact social sustainability by reducing employment opportunities and exacerbating economic inequality. Another ongoing challenge is data privacy and ethical concerns. The widespread use of AI and blockchain for sustainability monitoring raised questionable about data security, monitoring, and ethical corporate governance (Almusharraf, 2025; Qian et al., 2024). As companies increasingly rely on digital ecosystems to track environmental and social metrics, concerns about regulatory compliance, cybersecurity risks, and stakeholder trust are becoming increasingly apparent (Jensen, 2019). Companies can incorporate digital solutions into their strategic management practices to manage these trade-offs effectively. One method is to engage stakeholders via digital platforms, which allows for real-time collaboration with suppliers, customers, and regulators through decentralized networks. This fosters transparency and inclusive decision-making while ensuring that sustainability initiatives are in line with stakeholders' interests and help reduce potential conflicts (Miemczyk & Luzzini, 2018). Another important strategy is the introduction of adaptive sustainability practices using AI and IoT. Dynamic AI models enable companies to adapt their sustainability strategies based on real-time data, allowing them to remain flexible when balancing economic, environmental, and social priorities (Shou et al., 2019). In addition, proactive risk assessment using big data analytics helps companies anticipate potential sustainability trade-offs in advance. By using predictive analytics, organizations can identify risks and develop contingency plans that minimize disruption while meeting sustainability commitments (Hendiani et al., 2020). While digital ecosystems cannot completely eliminate all sustainability trade-offs, they provide companies with robust tools to address these challenges more effectively, thus building resilience in an increasingly complex business environment. Digital ecosystems are essential for reducing numerous conventional trade-offs associated with the TBL framework through improvements in efficiency, transparency, and adaptability. While digital technologies can help reduce economic, environmental, and social conflicts, they cannot eliminate trade-offs. Challenges remain, including significant implementation costs, job losses, and ethical concerns. A balanced approach that integrates digital solutions into strategic sustainability management is essential for companies to maintain their resilience, responsibility, and competitiveness in an increasingly complex global environment.

5.3.5 Regulatory framework and compliance

Incorporating sustainability principles based on the Triple Bottom Line (TBL) approach into digital ecosystems gives rise to intricate legal and regulatory challenges concerning economic, environmental, and social dimensions. Digital ecosystems driven by technologies like the Internet of Things (IoT), artificial intelligence (AI), and blockchain necessitate a novel assessment framework to tackle these complex challenges. To ensure the sustainability of digital ecosystems and compliance with international standards, the legal landscape must evolve to reconcile innovation with ethical and regulatory obligations.

The implementation of IoT technologies raises significant data privacy and security concerns. IoT systems facilitate the transmission of data, such as personal data, over digital networks, increasing the likelihood of profiling and unauthorized access. The European General Data Protection Regulation (GDPR) in Europe has raised the bar on how personal data needs to be protected, and this creates some tricky issue for the Internet of Things (Wolford, 2023; Fabiano, 2017). One big question is how to figure out who's responsible when multiple parties are sharing data in a digital setup. It's really important to set clear legal rules that spell out what each party needs to do to stay compliant with these data protection laws. Even though blockchain technology brings benefits like better transparency and security, it doesn't always fit well with the existing data protection laws. Since blockchain records cannot be modified, this poses a problem for the "right to be forgotten" under Article 17 of the GDPR, which gives individuals the right to request the erasure of their personal data (Wolford, 2023). Giannopoulou & Ferrari (2019) point out that companies issues in decentralized systems require a review of data ownership and legal liability, especially in public blockchain networks. Possible solutions include using restricted blockchains (which restrict access) or integrating off-chain solutions that enable data deletion while maintaining security.

The growing reliance on AI in digital ecosystems raises significant legal and ethical questions. To avoid bias, ensure accountability, and maintain human oversight, AI-driven decisions in supply chains, risk management, and sustainability reporting must comply with regulatory frameworks. The European Union's AI law sorts AI systems by how risky they are and sets strict rules for high-risk uses, like automated hiring and risk prediction in supply chains (*EU AI Act: first regulation on artificial intelligence | Topics | European Parliament*, 2023). One big issue is how clear and understandable the algorithms are. Numerous AI models, particularly those based on deep learning, operate as "black boxes," which complicates the interpretation of their decisions. Unfair evaluations of suppliers, discriminatory labor practices, or unintended biases in risk assessments can arise from a lack of transparency (Floridi, 2021). To ensure that human decision-makers can review and challenge AI-driven recommendations, regulatory frameworks should require the implementation of explainable AI (XAI) methods. Furthermore, the legal aspects of liability in AI-driven supply chains remain unclear. If an AI system leads to an incorrect or detrimental decision, determining the precise responsibility – be it the software provider or the implementing company- represents a major legal challenge (Smuha, 2021). Future regulations should establish responsibility frameworks to clarify the legal obligations of AI developers and users in supply chain management.

With the integration of sustainability principles into digital ecosystems, companies are faced with an increasing array of environmental and social regulations that oversee supply chains. The EU Sustainability Due Diligence Directive (CSDDD) requires companies to assess and reduce human rights and environmental risks in their supply chains. They are held legally accountable for any violations by their suppliers (*BMAS - Supply Chain Act*, n.d). Nevertheless, due to differing national regulations and the associated monitoring challenges, ensuring compliance with sustainability standards in global supply chains remains difficult. A major problem is the lack of standardized mechanisms for sustainability reporting. While frameworks such as the Global Reporting Initiative (GRI) and the Task Force on Climate Related Financial Disclosures (TCFD) provide guidance, these are not legally binding. As a result, sustainability reporting varies across industries (Bhambri & Paweloszek, 2024; KPMG International et al., 2020). Without global standards, companies have to contend with a patchwork of regulations, which drives up compliance costs and creates legal uncertainty. A major problem is the enforcement of environmental regulations in digital supply chains. Imported products are now being carbon priced based on their emissions as part of the European Green Deal and the Carbon Border Adjustment Mechanism (CBAM). This can lead to legal and financial problems for companies that do not fulfil the sustainability requirements (*The European Green Deal*, 2021). To comply with these regulations and avoid potential trade restrictions, advanced carbon tracking mechanisms should be integrated into digital ecosystems.

On top of that, there are worries about workers' rights and fair working conditions in digital supply chain management. While advanced technology can help manage workforce needs, they can also make job situations more unstable. It's crucial to protect workforce needs, they can also make job situations more unstable. It's crucial to protect workers from bias and discrimination in digital workplaces, as emphasized by the International Labor Organization (ILO) Convention No. 190 (*Convention C190 - Violence and Harassment Convention, 2019 (No. 190),* n.d.). For instance, AI systems that track employee performance might unintentionally cause issues with labor laws, potentially leading to unfair dismissals (Sachs et al., 2020). To ensure ethical working conditions and avoid systematic discrimination, regulations should require human oversight of automated labor management systems. The increasing reliance on gig and platform work within digital supply chains raises legal concerns regarding the classification of workers. Many individuals working in the gig economy are not covered by conventional labor protections, resulting in conflicts regarding pay, benefits, and job security (De Stefano, 2016). Future regulations must therefore create clear occupational health and safety provisions for workers on digital platforms that guarantee them fair remuneration and inclusion in social security.

To address these regulatory challenges, a comprehensive legal framework should be created that combines binding regulations with voluntary ethical guidelines. Kira et al. (2021) emphasize that interoperability standards, responsible AI governance, and strong data protection measures are essential for promoting sustainable digital ecosystems. Regulatory sandboxes that provide controlled frameworks for companies and policymakers to evaluate new regulations can help create adaptive legal frameworks that balance innovation and compliance (Köhler et al., 2021b). Regulation should be designed to ensure the profitability of digital ecosystems and their operation complies with the principles of environmental and social responsibility. This requires close cooperation between governments, technology developers, supply chain managers, and legal experts to harmonize laws across countries. Incorporating environmental standards and social justice principles contributes to achieving long-term sustainability goals and strengthening the resilience of global supply chains. Implementing the TBL approach in digital ecosystems involves complex legal and regulatory aspects and requires a comprehensive strategy that considers economic, environmental, and social dimensions. It's important to sort out issues like data protection for IoT and blockchain, transparency in AI, sustainability in supply chains, and workers' rights with clear rules and strong regulations. Companies can leverage the benefits of digital ecosystems while ensuring compliance with evolving ethical and legal standards by fostering cross-industry collaboration and implementing flexible legal strategies.

6. A holistic model for integrating digital ecosystems and sustainability in supply chain crisis management

The global economy is experiencing extraordinary turmoil due to geopolitical tensions, climate change, resource scarcity, and changing regulatory frameworks. Sustainability is becoming a must-have for businesses, policymakers, and society as a whole. Companies now have to deal with a tricky landscape where they can't just focus on reducing risks; they need to consider making money while also being socially responsible and protecting the environment in the long-term plans. The growing demands from stakeholders, regulators, and consumers for sustainable practices highlight the necessity of a transformative crisis management approach that aligns with the Triple Bottom Line principles (Elkington, 1997). As highlighted in previous chapters, conventional supply chain models are proving inadequate to manage the complex risks posed by climate related disruptions, market volatility, and regulatory changes. The rapid proliferation of digital technologies, including artificial intelligence, blockchain, digital twins, and the Internet of Things, presents a unique opportunity to improve supply chain resilience and advance sustainability goals. To incorporate these technologies effectively, a strategic approach is necessary to ensure that companies can enhance their real-time crisis response, predictive risk management, and adaptive decision-making while also fulfilling their environmental and social commitments (Ivanov & Dolgui, 2020; Xu et al., 2021). The convergence of digital transformation and sustainability is not just a technological shift; it signifies a fundamental reorganization of the functioning of global supply chains. To achieve this transformation, it is essential for companies to embrace a system-oriented approach that acknowledges the interconnection among economic performance, environmental sustainability, and social well-being (van Straelen et al., 2023). Companies that fail to integrate sustainability into their digital strategies risk not only operational inefficiencies but also regulatory non-compliance and reputational damage in an increasingly conscious market (Saberi et al., 2019). Against this backdrop, this chapter proposes a structured model that integrates digital ecosystems with sustainability-focused crisis management. This model aims to provide companies with a roadmap for future-proofing their operations by integrating theoretical insights from the TBL framework, the opportunities offered by new technologies, and the strategic requirements of resilient supply chains. The following sections explain the rationale for this integration, the key element of the proposed model, and its potential advantages and drawbacks. This chapter thus offers both academic and practical perspectives on how businesses utilize digital innovations to create supply chains that are resilient, sustainable, and prepared for the future.

6.1 Overview of the holistic model

Global supply chains are becoming more vulnerable to a range of crises, such as geopolitical conflicts, climate-related disruptions, and changes in regulations. Therefore, companies must go beyond traditional risk management strategies and adopt a resilient, data-driven approach that puts sustainability at its core (Ivanov & Dolgui, 2020; Sarkis, 2020). The emergence of digital ecosystems, which leverage artificial intelligence (AI), blockchain, the Internet of Things (IoT), and cloud computing, is fundamentally changing the way organizations manage these complexities. Despite the potential of these technologies, a comprehensive, structured framework that aligns digital transformation with sustainability and resilience goals remains underdeveloped.

To address this research gap, the holistic model for digital ecosystems and sustainability in supply chain crisis management is proposed as an organizational framework that enables companies to improve their crisis preparedness while strengthening their environmental and social responsibility. The approach to developing the model is extremely rigorous, and coherence between existing theoretical principles is ensured by a clear methodology. The process is based on Gregor’s (2006) theoretical adaptation, MacInnis (2011) concept integration, and Eisenhardt & Graebner’s (2007) framework transfer, which provides a structured basis for extending existing theories and applying them to new challenges in the field of supply chain resilience and sustainability.

This model is fundamentally based on the Triple Bottom Line Framework, which promotes the alignment of companies’ economic performance with their environmental and social commitments (Elkington, 1997). While TBL is a well-established concept, it does not inherently addresses the role of digital transformation. Following Gregor’s theoretical adaptation (2006), the TBL model is complemented by digital ecosystems as one of the main factors and drivers of resilience and sustainability. This method allows the original model structure to be retained while considering emerging technological dimensions that are more relevant to today’s challenges facing companies in global supply chain management.

In addition to the theoretical adaptation, the model utilizes MacInnis’ (2011) concept integration approach. This emphasizes the need to systematically integrate new ideas into existing frameworks to address complex interdisciplinary issues. In this context, insights from digitalization research, crisis management, and supply chain sustainability are brought together into a coherent model. The integration of AI, IoT and blockchain not only expands the scope of the TBL model but also changes the conceptualization of resilience and sustainability, making them more proactive and data-driven. Furthermore, the model follows the principle of framework transfer according to Eisenhardt & Graebner (2007), which examines how established theories can be applied to new fields to validate their relevance in different contexts. The TBL model was originally developed for sustainability management but is now also being used for crisis management in global supply chains. This shift is particularly significant in the digital age, as sustainability and resilience are increasingly intertwined through technology. By adapting the TBL to SCM crises, the model retains the core of its sustainability efforts while expanding its scope to serve as a tool for real-time risk mitigation and action.

A big part of this model is how it brings together the economic, social, and environmental needs of global supply chains using modern digital tools. With things like AI analytics, real-time tracking through IoT, and blockchain for transparency, companies can make better decisions and manage risks. This means they can adapt to surprises quickly while keeping costs in check and running smoothly (Ivanov & Dolgui, 2020). These tools also contribute to sustainability by tracking carbon footprints, ensuring ethical sourcing, and increasing efficiency. Blockchain, for example, helps ensure the accuracy of sustainability reports and reduce waste through intelligent data usage (Chang & Chen, 2020; Mangla et al.,2021), while IoT sensors provide real-time environmental information.

At the same time, the model strengthens social responsibility through greater transparency and accountability. AI audits and blockchain tracing can help uncover issues such as labor rights violations and ensure that companies comply with the law (Wang et al., 2019). Unlike traditional risk management, which is often reactive crises, this model combines data analytics, real-time monitoring, and intelligent automation to create supply chains that adapt and remain future-proof. AI-powered risk predictions enable companies to identify and prepare for potential issues. IoT enables them to identify supply chain vulnerabilities before they become major problems. Furthermore, blockchain ensures secure documentation, reduces fraud, promotes ethical procurement, and increases supplier accountability.

By seamlessly integrating these technologies, companies can transition from statically, linear supply chains to dynamic, self-adaptive networks that can respond to global uncertainties while supporting long-term sustainability goals. The model offers practical applications for various industries seeking to future-proof their supply chains. For example, retail and e-commerce companies can leverage AI-powered demand forecasting to minimize excess inventory and ensure ethical sourcing through blockchain based traceability. In pharmaceutical supply chains, blockchain-enabled cold chain logistics improved regulatory compliance and product authority. These applications demonstrate that digital ecosystems are essential not only for enhancing supply chain resilience but also for achieving sustainability and regulatory companies.

The holistic model for digital ecosystems and sustainability in supply chain crisis management serves as a strategic roadmap for organizations to improve crisis resilience, optimize supply chain efficiency, and fulfill sustainability commitments. By leveraging AI-powered predictive analytics, blockchain-based transparency mechanisms, and IoT-enabled real-time monitoring, companies can create a data-driven ecosystem that enables proactive risk mitigation, sustainability improvements, regulatory compliance, and better governance structures.

The following section examines the theoretical underpinnings of this integration, the key components of the proposed model, and its potential benefits and limitations. By synthesizing insights from the TBL framework, emerging digital technologies, and supply chain resilience strategies, this chapter provides both academic and practical perspectives on how organizations can harness digital innovations to develop resilient, sustainable, and future-ready supply chains.

6.2 Functionality and visualization

The holistic model for digital ecosystems and sustainability in supply chain management is designed to improve resilience while embedding sustainability into global supply chains. Organizations can tackle emerging risks, enhance efficiency, and guarantee adherence to regulations by merging the economic, social, and environmental aspects of the Triple Bottom Line with advanced digital ecosystems. This section entails a detailed breakdown of the model's structure and explains the key components, dependencies and technological synergies that drive supply chain optimization. Utilizing artificial intelligence, blockchain, the Internet of Things, and cloud computing, the model ensures that risk management, sustainability, and operational efficiency are not viewed as separate objectives, but as interconnected pillars of a resilient global supply chain. The model focuses on resilience and optimization, supported by a multi-layered technological framework. This includes real-time data integration, technology-enabled risk assessment, and a governance framework. This encompasses real-time data integration, risk evaluation aided by technology, and governance framework. This includes real-time data fusion, technology supported risk assessment and governance mechanisms that ensure transparency and compliance. The core of the innovation lies in the interplay of technologies within the digital ecosystem, where risk management, sustainability, and operational efficiency are viewed as integrated elements of a resilient global supply chain.

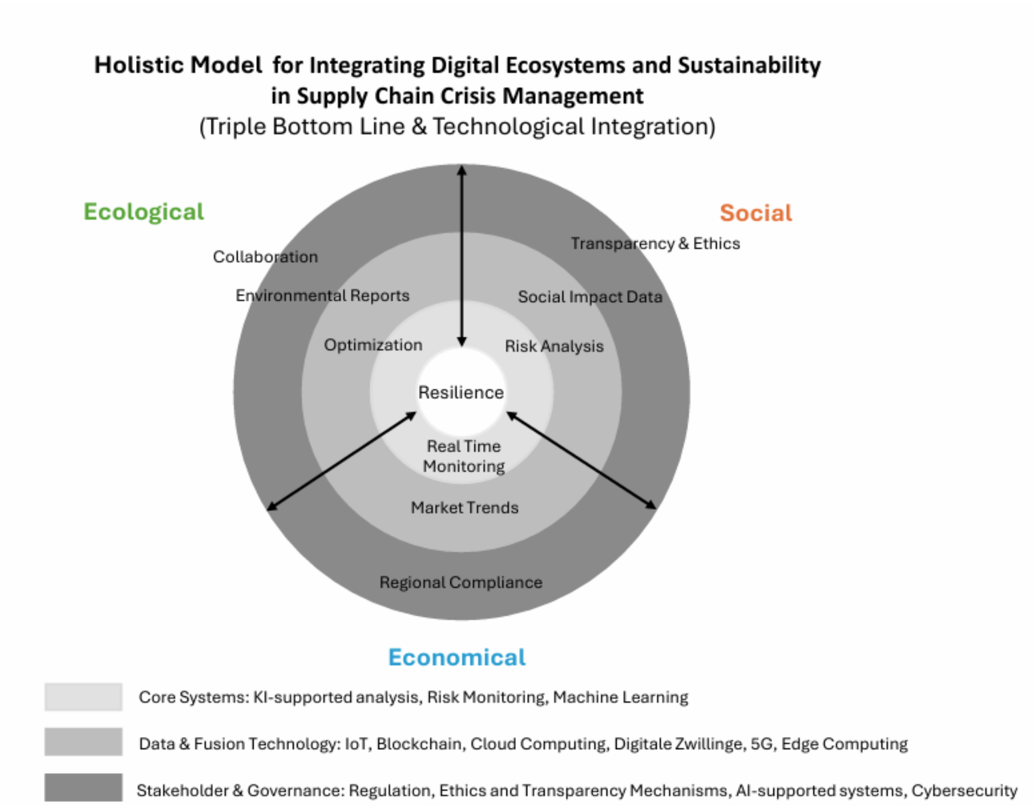

Figure 2: Holistic Model for Integrating Digital Ecosystems and Sustainability in Supply Chain Management (own illustration)

The model's structure is based on three interdependent levels that link technological and regulatory requirements with sustainability goals:

- The AI-driven core level: Enables predictive analytics, optimizes decision-making processes, and detects deviations in real time.
- The digital ecosystem layer: links IoT, blockchain, cloud technologies and edge computing to create a seamless, secure, and transparent database
- The governance and stakeholder layer: Ensures regulatory, ethical, and social standards that oblige companies to comply with global guidelines and create sustainable value.

6.2.1 Integration of the triple bottom line into the model

The economic aspect of the model focuses on market analysis, regional compliance, and risk minimization through digital intelligence. AI-supported forecasting models recognize geopolitical tensions, trade restrictions or supplier failures at an early stage, allowing companies to take preventative action (Baryannis et al., 2019). IoT-supported monitoring systems integrate these insights into procurement strategies in real time to avoid reactive crisis management. The model increases the efficiency of supplier negotiations and regulatory reporting processes through automated data processing and blockchain based contract management. Intelligent algorithms help balance cost optimization and resilience, ensuring that economic success does not come at the expense of crisis prevention (Baryannis et al., 2019).

The environmental component within the model ensures that sustainability is considered at every stage of the supply chain. Companies can measure their ecological footprint using real-time data on CO_2 emissions, water consumption, and energy efficiency. This data is captured using blockchain technology and secured in sustainability protocols to transparently demonstrate compliance with their ESG (environmental, social & governance) standards. This allows the model to actively contribute to resource conservation and emissions reduction. Fuel consumption can be minimized through AI-supported route optimization, and production waste can be reduced through intelligent inventory systems. Blockchain-based circular economy tracking also enables the tracking of material reuse and recycling measures, which goes beyond pure CO_2 reduction and promotes responsible resource management (Souza et al., 2024).

Ethical responsibility and compliance with international labor laws are ensured through the social dimension. AI-based text analysis systems continuously check for regulatory updates and ensure that companies comply with the standards of the International Labor Organization (ILO); the EU AI Regulation, and supply chain due diligence laws. Automated supplier audits and blockchain-based traceability systems can also ensure ethical procurement. These technologies identify risks relating to labor conditions, wage structures and safety standards throughout the supply chain. AI also analyses employee feedback and third-party supplier reports to highlight potential human rights violations at an early stage and enable proactive measures to be taken (Kira et al., 2021). The model also promotes direct collaboration between companies, regulatory authorities, and NGOs through digital stakeholder platforms. These ensure that ethical aspects play a central role in corporate decision-making processes.

6.2.2 Technological architecture of the model

The model is based on three harmonized technological levels that are linked to each other through continuous feedback mechanisms.

At its core, AI-supported decision-making systems form the foundation for an optimized and resilient supply chain. Machine learning enables risk detection and assessment, allowing companies to respond proactively to potential disruptions. Digital twins enable the precise simulation and optimization of supply chain processes (Farell, 2020; Tao et al., 2019). This helps avoid bottlenecks and utilize resource efficiency. In addition, the automated adaptation of production and logistics processes ensures dynamic control of the entire value chain, allowing companies to adapt flexibly to changing market conditions.

The second level, the digital ecosystem, serves as an interface for data fusion and technology integration. While blockchain technology ensures tamper-proof documentation of ESG standards, IoT sensors have the ability to capture key sustainability metrics such as CO_2 emission, energy consumption, and resource consumption in real time (Anan et al., 2017; Saberi et al., 2019). Cloud computing can enable scalable processing and global networking of supply chain information, providing companies with a reliable database for informed decision-making. 5G and edge computing also accelerated data processing by enabling decentralized, low-latency analytics directly at the data source (Liu et al., 2022c)

The third level, the governance and stakeholder level, focuses on ethical, regulatory and security related aspects, simplified through advanced technologies. AI-supported systems take over the continuous monitoring of legal requirements and ensure compliance with global regulations (Kira et al., 2021). Transparency mechanisms ensure that social and environmental standards are adhered to along the entire supply chain, enabling companies to effectively realize their sustainability and compliance goals. At the same time, comprehensive cyber security protocols protect sensitive supply chain data from external threats and ensure the integrity of all digital processes (Zhang et al., 2021).

The close interlinking of these three levels creates a holistic model that not only helps companies to make their supply chains more resilient and sustainable, but also to fulfil regulatory and ethical requirements efficiently.

6.2.3 Iterative optimization cycle of the model

A central component of the model is the continuous adaptation to dynamic market conditions, regulatory changes, and environmental factors. The process represented in this model consist of four interlocking and repetitive phases, which are closely intertwined.

In the first phase data is collected and monitored in order to capture relevant key performance indicators along the supply chains. IoT sensors provide real time information on CO_2 emissions, energy consumption, and transport efficiency, while blockchain technologies ensures tamper proof documentation of this data (Anan et al., 2017). Cloud systems enable the central storage and processing of global supply chain information with a comprehensive up to date data basis for the decision making (Liu et al., 2022a, Liu et al., 2022c).

The basis these technologies are building will be analyzed and optimized in the second phase, where AI-powered algorithms evaluate historical and current data to identify potential risks early on (Cho & Lee, 2021) . Using digital twins, companies can simulate and evaluate various scenarios and strategically optimize the results before implementation, while machine learning identifies supply chain inefficiencies and recommends targeted measures to reduce costs and improve sustainability (Ivanov & Dolgui, 2021, Ivanov et al., 2019, Farrell, 2020).

Adaptive implementation (Phase 3) leverages the insights from all previous phases. In this phase, 5G-enabled decision-making is used to dynamically adapt supply chain strategies to the situation (GEP, 2023). Companies can avoid potential bottlenecks and maximize resource utilization by optimizing logistics networks in real time. At the same time, automated compliance verification processes ensure compliance with all required regulations, thus meeting legal requirements, reducing legal risk, and increasing supply chain transparency (Kira et al., 2021).

In the final phase, continuous review and adjustment, sustainability metrics are regularly evaluated to measure progress towards environmental, economic, and social goals. Governance mechanisms ensure transparency and legal compliance by supporting companies in complying with ESG standards and international regulations. Using AI, feedback loops analyze supply chain evolution and enable continuous strategy optimization. This iterative cycle enables the model to ensure companies resilience to external disruptions while continuously improving their sustainability and efficiency goals.

6.3 Applications of the model in various supply chain scenarios

The holistic model for resilient and sustainable global supply chains is based on the integration of modern digital ecosystems and has the potential to be applied across industries. Although challenges regarding economic stability, environmental impact and social responsibility vary from industry to industry, the use of a intertwined ecosystem build out of sophisticated technologies can minimize risks, improve operational processes, and ensure ethical and regulatory standards (Craß et al., 2022). This section examines the model’s potential for improving resilience and sustainability in two hypothetical critical supply chain scenarios to demonstrate its broad applicability and transformative impact.

6.3.1 Applications in the automotive industry: Managing complexity and enhancing sustainability

The automotive sector relies on an extensive network of suppliers for raw materials, components and assemblies and operates in one of the most complex and globally interconnected supply chain networks (Ivanov & Dolgui, 2021). Due to its vulnerability to fluctuations in demand, resource scarcity and geopolitical disruptions, resilience is a key factor for long-term success in this industry. However, the need for sustainable production methods is growing due to regulatory pressures such as the EU Green Deal and strict CO_2 emission regulations (Köhler et al., 2021a). To counteract these challenges, AI-based analytics, blockchain-based traceability systems and IoT-based monitoring solutions are increasingly being used by automotive companies to support risk prediction, supply chain optimization and compliance regulations. Such integration and combination of new technologies united in a digital ecosystem, as described in the model, should thus strengthen the resilience and sustainability of the supply chain.

Applying the model developed in this chapter, AI-powered predictive analytics would play a central role recognizing risks in the supply chain and developing proactive strategies at the core level of the system. At this core level large amounts of historical and current data would already be analyzed by machine learning algorithms to predict disruptions before they occur. A relatively recent example is the semiconductor shortage, where AI-supported demand forecasts have helped car manufacturers to identify supply bottlenecks at an early stage, adapt procurement strategies accordingly and minimize production delays and financial losses (Xu et al., 2021). Systematic integration of such predictive analyses, as outlined in the proposed model, should strengthen the industry's ability to respond to future disruptions and turn them to its advantage.

Technologies required for the data and technology fusion level, which ensure transparency and traceability along the supply chain, like blockchain, IoT and cloud computing are already implemented in most automotive manufacturers. Companies like BMW and Tesla have already blockchain-based systems in place to enable tamper-proof monitoring of raw materials such as lithium and cobalt, thereby complying with ethical mining regulations and reducing the risk of personal injury (Köhler & Pizzol, 2020; Köhler et al., 2021b). At the same time, IoT sensors provide real-time data on emissions, energy consumption and production efficiency, while cloud-based platforms enable global data utilization on the network (Anan et al., 2017, Dubey et al. 2020). By consistently networking these technologies in a unified digital ecosystem, the automotive industry could carry out even more precise sustainability analyses, better identify risks and further increase its efficiency. An opportunity could be created through the combination of this data-driven intelligence alongside AI-powered decision making to improve compliance with sustainability regulations, as well as resilience to unforeseen disruptions.

At stakeholder and governance level, car manufacturers are already using AI-supported logistics processes to make their supply chain more stable and flexible. Companies such as DHL or Maersk are already using AI to continuously optimize their delivery networks so that they can spontaneously reroute shipments if a bottleneck arises somewhere (Ivanov & Dolgui, 2020), which could also be useful in the automotive industry. In the future, new technologies such as 5G and edge computing could significantly speed up this process even further, as data can be processed directly on site. This ensures faster reactions and better decision in real time (GEP, 2023, Appius et al., 2021). Another important point is security since sensitive data is in transit and must be well protected in order to reduce the risk of supply chain disruptions through cyberattacks. Another exiting approach from a car manufacturers point of view is the use of so called digital twins, which are virtual images of real processes or supply chains. Some car manufacturers are already using such simulations to run through different scenarios and find out what works best in an emergency. If car manufacturers were to use such digital models consistently, it would be possible to make improve decision making by playing through problems and alternatives before they arise. This means that a comprehensive implementation of digital twins as part of the proposed model should help to evaluate different procurement strategies and logistics routes even more accurately and thus anticipate future disruptions at an early stage.

Overall, the automotive industry is already using a variety of digital technologies to optimize its supply chains. If they would integrate these technologies into a digital ecosystem, like depicted in Figure 2, they could further improve resilience, efficiency and sustainability. The multi-level structure of the proposed model could enable a seamless alignment between technological innovation, sustainability and regulatory requirements, which would lead companies to react more quickly to crises, minimize economic losses and ensure stable production processes in the long term, even in the face of increasing volatility on the global market.

6.3.2 Application in the agri-food sector: Ensuring sustainability and resilience in perishable supply chains

The agri-food sector is another sector facing numerous challenges, particularly in regards to food security, sustainability, and climate vulnerability (Alaba et al., 2024; Farrell, 2020; Guidani et al., 2024). To ensure long-term resilience, risks such as climate change, market volatility and changing regulations must be proactively managed and sustainability considerations integrated (Xu et al., 2021). Many organizations are already exploiting a variety of digital technologies to address these challenges. However, integrating such a holistic model could also have a potential positive impact in this specific sector as well.

Here, AI-powered predictive analytics also plays a key role at the core of the model. Since food is highly perishable, it requires accurate forecasts, crop yields, and market trends to adapt production and disruption strategies to their supply chain (Alaba et al., 2024; Saberi et al., 2019). A prominent example of Walmart’s AI-powered demand forecasting systems, which optimize food distribution, minimize food waste, and increase logistic efficiency (Farell, 2020). In the agricultural and food sector, greater integration could improve technologies such as forecast accuracy and enable companies to respond more quickly to changing conditions. This could prevent bottlenecks, utilize production capacity more efficiently, and strengthen the entire supply chain.

At the data and technology level, a combination of blockchain, IoT, cloud computing, and digital twins would enable better traceability, compliance, and sustainability monitoring. Blockchain-based transparency systems, such as those deployed by Nestlé and Carrefour through IBM Food trust, could enable food from producer to fork, ensure food safety, and verify organic certifications to prevent, among other things, fraud (Seregin, 2023; Köhler et al., 2020). These modern technologies could ensure faster traceability of contamination and more efficient recall procedures in this industry, thereby reducing the risk of food poisoning. IoT sensors, already deployed in some agricultural supply chains, are already collecting real-time data on soil quality, water consumption, and greenhouse gas emissions. This enables more precise agricultural practices that optimize resource use and ensure compliance with environmental regulations (Tian, 2016; Xu et al., 2021). The extended integration of these technologies into the model could enable even more precise sustainability analyses and improve traceability across the entire value chain. Digital twins, which are already used to simulate agricultural production scenarios, could be further developed to analyze the effects of climatic conditions in even greater detail. This would enable farmers to adapt their cultivation and irrigation strategies even more specifically to changing environmental factors.

At the level of stakeholders and governance, AI-driven decision support systems and compliance checks are helping to meet sustainability laws and food safety rules. These AI models provide advice on topics such as fertilization, irrigation and harvesting practices to increase crop yields while protecting the environment (Alaba et al., 2024). The use of 5G and edge computing could help farms process real-time data faster, enabling them to respond more quickly to weather changes and supply chain issues. Better cybersecurity measures can also help protect important agricultural data and reduce the risk of fraud or data manipulation (Zhang et al., 2021).

The technologies already deployed to optimize agricultural and food supply chains are already showing success (Guidani et al., 2024). However, consistent integration into the holistic model could further strengthen resilience, reduce food losses, and achieve even better alignment with global sustainability goals. The multi-layered structure of this model would therefore ensure a seamless integration of technological progress, regulatory requirements, and environmental responsibility. This would enable food manufacturers and retailers to further increase their efficiency, minimize waste even more and sustainably improve food safety in an increasingly uncertain world.

6.3.3 Cross-industry impact of digital ecosystems

By combining sustainability and digital ecosystems, the model developed in this thesis could offer companies an optimal solution for crisis management in the event of supply chain disruptions, as it systematically integrates innovative technologies to increase resilience, efficiency, and sustainability. By linking advanced technologies into a unified, interconnected structure, companies could increase their resilience to disruptions, achieve efficiency gains, and better pursue their sustainability goals, since digital ecosystems offer a promising approach to address the challenges (Fornasiero & Tolio, 2024; Holzwarth et al., 2022). For example, demand forecasting and inventory management could be improved by analyzing historical data and trends, which could lead to an optimized supply chain (Downie & Finn, 2024). Blockchain-based transparency solutions would ensure more reliable traceability of products and compliance with ethical and regulatory standards. The integration of blockchain with IoT devices could hypothetically enable the secure tracking of products in real time and improve transparency along the entire supply chain (Moudoud et al., 2022). Likewise, the IoT-supported real-time monitoring should improve resource utilization, optimize processes, and strengthen the data basis for strategic decisions. Finally, by using IoT sensors, for example, companies can monitor the condition of machines and devices and predict potential failures, leading to a reduction in unplanned downtime (SmartMaker, n.d.).

This structured combination of technologies in a digital ecosystem should enable companies to make data-based decisions faster, make supply chains more stable and coordinate collaboration with stakeholders more efficiently. In addition, increasing connectivity through 5G and edge computing supports the processing of large amounts of data in real time, allowing companies to react more flexibly to market changes and external influences (GEP, 2023). To increase security and transparency in financial transactions and automate manual tasks, a combination of AI and blockchain can be effective, as it can lead to a reduction in operating costs (*Edge-Computing-Lösungen | IBM*, n.d.; Downie & Finn, 2024).

The scope of the model for integrating digital ecosystems and sustainability into supply chain management has the potential to extend across various industries, from manufacturing to retail and logistics to healthcare. Regardless of the industry, implementing this holistic model can help promote innovation in a targeted manner, minimize operational risks, and ensure sustainable value creation. Companies that embrace comprehensive digitalization and networking early on can strengthen their long-term competitiveness and adaptability to economic, technological, and regulatory conditions. The Dibichain project, for example, shows how the integration of blockchain, AI and IoT helps to create a digital twin for products that integrates information on products and materials from all parties along the supply chain, thereby increasing transparency and sustainability (Blog, 2023).

6.4 Limitations of the model and future research direction

While the increasing digitalization of global supply chains offers significant potential for crisis management, it also presents several challenges. As a result, the implementation of digital ecosystems for resilient and sustainable supply chain management is associated with technological limitations, uncertainties regarding data availability, regulatory hurdles, and ethical issues (Ivanov, 2021). While advances in artificial intelligence (AI), blockchain and the Internet of Things (IoT) can improve risk management, many organizations face the challenge of deploying these technologies effectively in complex and often fragmented supply networks (Saberi et al., 2019).

6.4.1 Limitation of the model

A fundamental limitation of digital, AI-supported supply chains is their dependence on high-quality, real-time data. The consistency and reliability of available data sets are crucial for the effectiveness of forecasting models, risk analyses, and optimization algorithms (Xu et al., 2021; Saberi et al., 2019). However, practice shows that many supply chains are characterized by fragmented data sources, inconsistent reporting standards, and a lack of transparency, which in this context would lead to incomplete and distorted information (Xu et al., 2021; Saberi et al., 2019). Companies that rely on outdated IT infrastructures or are reluctant to share data for competitive and security reasons make it difficult to seamlessly integrate digital crisis management solutions (Ivanov & Dolgui, 2020). In addition, merging heterogeneous data streams - for example from IoT sensors, blockchain transactions and AI-supported analyses - poses an enormous technical challenge, especially because supply chains involve numerous players with different regulatory requirements (Kshetri, 2018). The lack of standardization in data management leads to interoperability issues and hinders the smooth use of digital technologies for overarching risk management (Köhler et al., 2021b).

Even though AI-supported decision-making processes can increase the efficiency and resilience of supply chains, they bring new challenges, especially in terms of computational complexity and ethical risks. Many of the AI models used are so-called ‘black box’ systems whose decision-making logic is difficult for crisis management to understand (Floridi, 2021). This lack of explainability can undermine trust in AI-based risk analyses, supplier assessments and sustainability certifications, which in turn can cause regulatory problems (Sarkis, 2020). There is also a risk that AI systems could reinforce existing systemic biases, thereby fostering regional disparities, socioeconomic inequalities, or industry-specific discrimination that have emerged based on historical training data. This could result in the perpetuation of unfair labor practices, violation of environmental regulations, or discriminatory pricing strategies (Kira et al., 2021;Smuha, 2021; Köhler et al., 2021b). Without robust AI governance, there is a risk that digital ecosystems will reinforce existing inequalities instead of reducing them. Future research must therefore focus more on the development of ethical AI models, bias minimization, and improved accountability mechanisms to ensure fair and responsible supply chain decisions (Floridi, 2021).

The regulatory landscape for AI-supported supply chains is evolving dynamically, which means that companies are constantly confronted with new legal requirements. While regulatory initiatives such as the EU Supply Chain Act and the EU AI Act set stricter compliance requirements, harmonizing these regulations at a global level remains a challenge (*BMAS - Supply Chain Act*, n.d.; *EU AI Act: first regulation on artificial intelligence | Topics | European Parliament*, 2023; Köhler et al., 2021b). Multinational companies have to deal with different regional interpretations of regulations, which makes long-term strategic planning more difficult (Saberi et al., 2019). Another problem is that many regulatory approaches are reactive rather than proactive, which leads to uncertainty among companies regarding the future development of AI-based sustainability strategies. In addition, new regulations increase the requirements for data protection, liability for automated decisions and standards for environmental reporting (Floridi, 2021). In particular, small and medium-sized enterprises (SMEs) and suppliers from resource-poor regions are struggling with the increasing digitalization requirements, which limits the broad applicability of digital ecosystems. Future research should therefore focus on scalable, regionally adapted AI governance models and flexible regulatory adaptation strategies to enable inclusive and global implementation (Ivanov, 2021).

Although digital ecosystems can contribute to increasing resilience in the short term through real-time monitoring and AI-supported decision-making, their long-term effectiveness in systemic crises remains uncertain. This is because they can be influenced by a variety of factors, both negatively and positively (Ivanov & Dolgui, 2020). These factors do not necessarily have to be external nature, but can also have other origins, as described in chapter 2.3.1. AI-supported forecasting models are based on historical data, which limits their ability to respond appropriately to unforeseen crises such as pandemics or global trade conflicts (Xu et al., 2021). Another risk is the overreliance on automated decision-making without sufficient human oversight, as AI-supported systems focus on short-term efficiency improvements and cost optimization, while long-term sustainability or ethical aspects may not be considered (Sarkis, 2020). This implies that future research should consider hybrid decision-making models to combine AI-based efficiency with qualitative scenario analysis and ethical supply chain management. This could ensure that economic, social and ecological factors are equally included in the decision-making process (Geissdoerfer et al., 2017)

6.4.2 Future research directions

In order to overcome the identified limitations in crisis management and improve the effectiveness of the model, further research is needed, particularly with regard to the integration and customization of digital ecosystems. An important area of research is the standardization and interoperability of data, as fragmented and inconsistent data is the biggest challenge for AI-supported optimization in crisis situations (Köhler et al., 2021b). The introduction of standardized, cross-industry blockchain protocols for verified sustainability reporting and supplier transparency could increase trust in regulatory compliance and enable secure data exchange across global networks (Saberi et al., 2019). In addition, research should continuously work on the development of explainable AI (XAI : Explainable Artificial Intelligence) that enables crisis managers to interpret AI-generated recommendations and adjust them, if necessary, rather than blindly trusting opaque algorithmic results (Floridi, 2021). In crisis situations, the development of bias detection mechanisms in AI-powered solutions should also be prioritized to ensure that AI does not lead to unfair or discriminatory decisions (Sarkis, 2020). Greater harmonization of regulatory frameworks and technology development is also needed to reduce legal uncertainties and increase the resilience of supply chains in crisis (Köhler et al., 2021b). Research initiatives such as regulatory sandboxes could help companies and regulators to test new regulatory approaches for AI-embedded supply chains in real-life crisis scenarios and remove uncertainties before new laws are fully implemented. Future research should focus on hybrid decision-making models that combine AI with human intuition and experience to maximize the impact of AI on crisis management while ensuring human control at critical moments (Sarkis et al., 2020). They should develop resource-efficient, lighter AI models for regions with limited digital infrastructure to enable inclusive crisis management in emerging economies (Saberi et al., 2019). The development of the digital ecosystem in crisis management offers great potential, but obstacles in the area of data quality, regulatory uncertainties, AI transparency and adaptability to unexpected crises must be overcome. The central point should be to close these gaps to ensure that AI-enabled supply chains become more efficient and resilient while navigating an increasingly complex global environment in an ethical and sustainable manner.

7. Discussion & results

This analysis examines how crisis management of multinational companies can not only reduce the impact of global supply chain disruptions by integrating new digital ecosystems, but also promote sustainability goals and increase resilience in the long term. The analysis displays the central role which digital technologies such as artificial intelligence, blockchain and IoT are playing in the transformation of global supply chains. They create economic, social and environmental benefits by enabling more precise risk identification, improved transparency along the supply chain and data-driven optimization processes.

The results of the study confirm that the implementation of digital ecosystems contributes to a significant reduction in the negative impact of global supply chain disruptions. Early warning systems based on AI make it possible to predictively analyze risks, allowing companies to react proactively to potential disruptions. This is in line with the findings of Ivanov & Dolgui (2020), which show that digital technologies provide greater operational stability in crisis situations through real-time data processing. In addition, the study shows that AI-supported decision-making models and automation processes contribute significantly to reducing inefficiencies by enabling better resource utilization and anticipating supply bottlenecks at an early stage. These findings support earlier work by Saberi et al. (2019), who emphasize that digital technologies can contribute not only to increasing efficiency, but also to promoting sustainability goals within supply chains. The research findings also show that the integration of digital ecosystems contributes significantly to promoting sustainability in global supply chains. Blockchain technologies create increased transparency by providing tamper-proof data on the origin and sustainability of products. This helps companies more efficiently comply with regulatory requirements – such as the European Supply Chain Act or the EU AI Act – while promoting responsible procurement strategies (Floridi, 2021). In particular, the integration of blockchain into IoT applications enables detailed monitoring of emissions, reducing consumption, and delivery processes, enabling companies to take targeted, environmentally friendly measures. However, the study also highlights trade-offs between resilience, sustainability, and technological implementation. For example, while higher inventory levels increase companies resilience in the short term, they conflict with environmental sustainability goals by leading to increased resource utilization and higher storage costs (Sarkis, 2020). A rise in automation can improve efficiency but potentially negatively impact social sustainability aspects such as job security or fair working conditions in the supply chain (Floridi, 2021). This quandary requires a differentiated approach for implementation strategies to ensure a balance between economic stability, environmental responsibility, and social justice. Another point of discussion concerns regulatory challenges. While digital technologies enable significant advances in crisis management and promoting sustainability, heterogeneous regulatory requirements and fragmented legal frameworks in the different countries continue to create significant obstacles to the global scaling of these solutions. Which is why companies should invest in compliance strategies to meet constantly evolving legal requirements (Köhler et al., 2021b) The impact of these findings for academia and practice are far reaching. Theoretically, the study contributes to current research by demonstrating that digital technologies should not be viewed in isolation, but as integrated systems that simultaneously promote resilience and sustainability. This necessitates the development of holistic digital transformation strategies that are aligned with both risk mitigation and long-term sustainability goals. These results demonstrate that the integration of new digital ecosystems can make a significant contribution to increasing resilience and promoting sustainability in global supply chains. They also demonstrate that technological innovations must be embedded in a broader strategic, regulatory, and ethical context and therefore cannot be viewed in isolation (Fornasiero & Tolio, 2024; Roux et al., 2023). The challenge for companies is to shape digital transformation in such a way that it addresses both short-term crisis management and long-term sustainability goals, which is a balancing act that requires technological, organizational and strategic rethinking.

This master's thesis thus contributes to the existing literature by analyzing the isolated effects of digital technologies on supply chain resilience, and examining their integrative role in interaction with sustainability goals and regulation requirements. The difference of the existing literature is the holistic analysis approach, which systematically links the technological, ecological, and social dimensions of resilience and provides practical implications for a strategically orientated digital transformation. Building on these findings, the following and final chapter summarizes the main conclusion of the work, reflects on the limitations of the investigation, and provides an outlook on future research perspectives.

8. Conclusion, limitations & outlook

This study investigated how crisis management in multinational companies can not only reduce the impact of global supply chain disruptions by integrating new digital ecosystems but also promote sustainability goals and increase resilience in the long term. The results demonstrate that the use of artificial intelligence, blockchain, and IoT technologies within a digital ecosystem plays a key role in increasing transparency, identifying risks early, and implementing adaptive strategies (Fornasiero & Tolio, 2024, Holzwarth et al., 2022). By combining real-time data processing, predictive analytics, and automated decision-making, companies can respond more quickly to unexpected crises while simultaneously developing sustainable, resource-efficient business models. However, the effective implementation of these technologies remains challenging, particularly due to technological limitations, regulatory uncertainties, and ethical issues (Wang et al., 2018).

Despite the promising findings, this study is subject to several limitations. A key limitation is its reliance on high-quality, interoperable data, which is essential for reliable AI-supported decision-making. In practice, however, significant data gaps exist that can lead to biases or unreliable predictions. Furthermore, the integration of new technologies remains associated with significant investment costs for many companies, especially for small and medium-sized enterprises that lack the necessary IT infrastructure or expertise. Another challenge is the dynamic nature of regulatory requirements: While regulatory frameworks such as the EU AI Act or the Supply Chain Due Diligence Act force companies to adapt to stricter regulations, uniform global standards are lacking, further complicating the implementation of complex digital ecosystems. Finally, the impact of long-term, systemic crises – such as geopolitical conflicts or climate-related disruptions – on the performance of digital resilience models has not yet been fully researched (Cho & Lee, 2021; Kouvelis et al., 2019; Sodhi & Tang, 2021).

Against this backdrop, several key research and development areas emerge to further optimize the efficiency and scalability of AI-supported supply chain models. First, future research should increasingly focus on improving the interoperability and standardization of data protocols to enable seamless integration of digital systems across different actors and industries. Second, further studies are needed to systematically analyze ethical and social aspects of AI integration in the supply chain—particularly with regard to bias reduction, transparent decision-making processes, and human-centered AI models. Third, more intensive collaboration between academia, business, and politics is required to minimize regulatory uncertainties and create an innovation-friendly framework for scaling digital resilience strategies. Finally, research on the application of AI in the context of the circular economy could be further intensified to combine sustainable supply chain strategies with data-driven optimization models and align long-term economic, ecological, and social sustainability goals.

The findings of this study provide clear recommendations for the management of multinational companies. First, companies should invest more heavily in digital infrastructure and AI-based decision-making models to increase their resilience to global crises. This requires not only technological investment but also the training of employees in the use of data-driven systems. Second, targeted risk management is essential, combining digital early warning systems with traditional, experience-based approaches to ensure balanced decision-making. Third, companies should respond early to regulatory developments by establishing transparent, ethical AI governance structures to minimize compliance risks. Finally, close collaboration with suppliers and external partners will be crucial for successfully implementing digital ecosystems across the entire value chain and sustainably improving both resilience and sustainability.

In summary, this study demonstrates that integrating new digital ecosystems into crisis management in global supply chains offers significant potential for addressing disruptions and promoting sustainable business models. At the same time, challenges in data quality, technological infrastructure, and regulatory complexity emerge that must be addressed through targeted research and practical innovation strategies. In an increasingly interconnected and volatile world, the ability to link digital resilience strategies with sustainability goals will represent a decisive competitive advantage – both for individual companies and for the global economy as a whole.

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Appendix

Literature matrix

Sources	Crisis management in multinational companies	Digital ecosystems and new technoogy	sustainabilit in supply chains	Resilience of the supply chain
Aditya, K., Chakraborty, S., Dahire, A., Kumari, A., & Milanova, M. (2024). Integrating Blockchain, IoT, and AI in Supply Chain Management. In Blockchain, IoT, and AI Technologies for Supply Chain Management: Apply Emerging	☐	☑	☐	☐
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