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IT-Enabled Supply Chain Resilience in Global Logistics Operations: A Scenario-Based Informatics and Service-System Coordination Framework

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Abstract. Global supply chains are highly interconnected – material flows, information flows, digital platforms, suppliers, logistics providers, and customers are more and more interdependent with each other in the form of logistics service systems. In times of geopolitical uncertainty, a pandemic outbreak, cyber threats, demand fluctuations and technological downtime, supply chain resilience goes beyond flexibility and redundancy of resources. It demands a comprehensive logistics informatics system, an instant service coordination and adaptive digital decision-making. This study constructs an IT-supported supply chain resilience model, which combines enterprise resource planning systems, Internet of Things monitoring, cloud platforms, blockchain traceability, big data analytics and digital twin technologies. The research uses scenario analysis to assess the impact of digital integration on recovery time, lead time, transparency and adaptability and service continuity in global logistics operations. The empirical framework is based on selected multinational companies and the indicators of resilience are the Index of Digitalization of Supply Chains, Scenario Stability Unit and Index of Supply Chain Adaptability. Results indicate that digitally integrated logistics systems are more resilient in the event of an economic shock and technology failure, as well as combined disruptions. The highest resilience effect is realized when IT tools are used as an integrated service-system architecture as opposed to individual technological services. In this study, an integrated model for digital coordination of resilient supply chain operations is proposed, which is also a contribution to the field of logistics informatics and service science.

Keywords: Supply Chain Resilience; Logistics Informatics; Service-System Model; Digital Logistics Operations; Scenario Analysis; IT Integration; Digital Transformation; Risk Management

1. Introduction

Global supply chains have become complex and are highly interconnected, involving manufacturers, suppliers, logistics providers, warehouses, retailers, digital platforms and end consumers from various countries and economic zones. The systems are not only about goods transport anymore, but in today's logistics landscape, the flow of information, digital coordination, predictive analytics and synchronized service interactions between actors in the supply chain play an equally important role. Trade and production processes are highly globalized and supply chains have become increasingly complex to operate, while at the same time facing greater threats to disruption, uncertainty and systemic risks. This has led to the ability to withstand the shocks and stresses of logistics operations being one of the main strategic concerns of companies in global markets (Queiroz et al., 2019; Gunasekaran et al., 2017). The fragility of international supply chains to external shocks has been shown in recent world crises. The COVID-19 pandemic, geopolitical instability, military conflict, cyberattacks, inflation, and raw material shortages and disruption in transport infrastructure have shown to be significant constraints in the implementation of traditional approaches to supply chain management. In many sectors, disruptions in one area of the globe quickly spread to multi-layer supply chains leading to cascading failures in production, transport and distribution networks. These delays caused substantial cost, delivery delays, stock-outs and reduced service quality. In extremely dynamic markets, organizations have come to understand that the conventional efficiency-focused approaches to supply chain management, driven by cost minimization, are not enough (Ivanov & Dolgui, 2021; Saberi et al., 2019).

In this setting, the notion of supply chain resilience has emerged as a key focus in the field of logistics, informatics and service science research. Classical resilience studies define supply chain resilience as the adaptive capability of the supply chain to prepare for, respond to and recover from disruptions while maintaining continuity of operations (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009; Wieland & Wallenburg, 2013). Supply chain resilience is defined as the capacity of a supply chain to withstand disruptions, absorb shocks, keep supply chain operations running and recover within acceptable time limits following an unexpected event. Modern resilient supply chains should prove to be adaptive, flexible, transparent and responsive to the external dynamic environment. Thus, resilience is not just about recovery, but should be read as the ability to coordinate, to operate synchronously, and also adaptively in order to make decisions, predictively (Dubey et al., 2021; Ivanov et al., 2019). With economic systems becoming increasingly digital, how supply chain resilience is created has substantially shifted. Information technologies are becoming the backbone of logistics coordination, logistics monitoring and logistics strategic planning. For organisations, the opportunities include the ability to enable fragmented logistics processes to become part of a single digital system through the use of enterprise resource planning systems, cloud computing, the Internet of Things, blockchain platforms, and artificial intelligence and big data analytics. The technologies enable the real-time monitoring, automated decision-making, and predictive forecasting/service coordination of various supply chain actors (Ben-Daya et al., 2020). In today's era of modern logistics, big data analytics and artificial intelligence have taken a crucial role in the transformation of modern logistics. The advanced analytical systems enable businesses to process huge amounts of their operational data and uncover the underlying trends and patterns associated with demand swings, stockouts, supply instability and transportation bottlenecks. AI can model disruption and optimise logistics routes and support adaptive inventory management strategies. This means that digital analytics shift the nature of supply chain management from solving problems reactively to coordinating it proactively and predictively (Zhang et al., 2021; Idrissi et al., 2024). Concurrently, current research shows a number of relevant restraints. First, many researchers analyze individual technologies and do not focus on an integrated logistics informatics architecture. Secondly, most empirical research is limited to individual industries or particular geographic areas and therefore does not enable results to be applied to the global inter-related logistics system. Third, past studies tend to focus on the technology aspects of digital transformation, and fail to address how service-system coordination, interoperability and operational

synchronization can contribute to resilience, especially. Lastly, existing analytical tools are mostly static, and fail to fully represent the dynamic characteristics of disruptions, adaptive recovery processes and the multi-risk operational environments. These constraints highlight the need to establish a service system perspective with a digital technology and logistics operations-resilient relationship. Resilience in today's logistics environments is not just a matter of having to put in place individual pieces of IT, but also requires organizations to proactively create usable and efficient digital infrastructures that combine the various elements of information flow, operational coordination, and predictive analytics. Thus, the efficiency of supply chain resilience increasingly relies on the ability to use logistics informatics architecture, as well as the synchronisation between supply chain actors, which is increasingly digital (Papadopoulos et al., 2021). This research is intended to fill these research gaps by developing an IT enabled Supply Chain Resilience model in the context of Logistics Informatics and Service-system Coordination principles. This study examines the impact of integrated digital technologies on operational continuity, adaptive response capability and resilience performance in worldwide logistics operations. This is in contrast to the traditional view of a technology being assessed individually, where the research takes a holistic view of digital transformation as a system of information exchange, predictive coordination and synchronization of logistics. An economic shock, a failure in technology and both shocks combined are applied to scenario analysis to examine the impact of digital integration in these scenarios. In order to reach the purpose of the research, the following research questions were developed:

RQ1. What is the impact of information technologies that are integrated in global supply chain systems on operational resilience and adaptive recovery capability?

RQ2. What is the role of Logistics Informatics and Coordinating logistics services in the enhancement of logistics operations transparency, synchronization and continuity?

RQ3. What is the impact of AI Analytics, IoT monitoring and blockchain traceability on predictive coordination and disruption management in the supply chain?

RQ4. What is the intersection of digital technologies that offer the greatest resilience overall, both in economic and technological disruption scenarios?

The remaining of the paper is organised as follows: The literature review and theoretical grounds of the research hypotheses is provided in section 2. The methodological framework and scenario analysis approach is described in section 3. The findings of the empirical research and impact of digital technologies on resilient logistics operations are discussed and evaluated in Section 4. Finally, Section 5 presents the key findings, theory implications and practical implications for adaptive supply chain management in digitally integrated environments.

2. Literature Review

Scholarly interest in the supply chain resilience and digital transformation has grown substantially in the midst of the global economic system's rapid transformation, the growth of digital platforms and the rising complexity of international logistics networks. Today's supply chains operate in very uncertain conditions: geopolitical, cyber, climate change, transportation and international demand. In these cases, the traditional approach to operations optimization and cost reduction is not enough to ensure the sustainable logistics performance. However, adaptive supply chain systems that are more information-driven and digitally coordinated, with the ability to ensure the continuity of operations when external shocks hit are increasingly sought after by organizations (Queiroz et al., 2020; Wamba et al., 2020). The logistics processes are becoming more digital, significantly altering the processes by which supply chain resilience is being created. Information technologies will increasingly transform the supply chains into a new form of interconnected logistics service ecosystems, and operational effectiveness will increasingly depend on the ability to exchange information in real-time and to coordinate and synchronize decisions made based upon the information in advance (Ivanov & Dolgui, 2021). In addition to operational automation, the practical value of the above technologies is related to the

creation of integrated logistics/informatics architectures that enables the adaptation of response and dynamism coordination in the face of uncertainty. Meanwhile, it is known that some of the previous scientific works have some theoretical and methodological deficiencies. A lot of studies are directed at single technologies and not towards integrated digital ecosystems. Few studies examine the adoption of digital ecosystems as opposed to individual technologies. Second, many empirical studies are industry or regional logistics system specific, and so do not allow for the extent to which conclusions can be drawn for global supply networks. Thirdly, few analytical models consider technological efficiency and analyse the interoperability and the synchronisation of information and the coordination of services to a lesser extent, without taking into account mechanisms to ensure the desired resilience in multi-tier logistics operations. Furthermore, a considerable amount of research is descriptive, and does not have a well-developed scenario-based and/or predictive analytical approach that can be used to assess resilience under complex disruption conditions (Dubey et al., 2020; Kache & Seuring, 2017). A pending issue in this context is what constitutes the link between technological integration and organizational adaptability. Digital technologies, however, have a great deal of analytical and operational advantages, but they also heavily depend on managerial skills, inter-organizational coordination and the ability to integrate the various information systems into a digital system. This has resulted in an expanding interest in interdisciplinary research on logistics informatics and how to integrate adaptive resilience management into a single framework of analysis (Papadopoulos et al., 2021; Ivanov & Dolgui, 2020). The importance of the present study is further justified by the increasing strategic importance of resilient supply chains for sustainability in the global economy. The logistical functions have been disrupted in recent years, with a direct impact on the continuity of manufacturing activities, the quality of services, the stability of trade and satisfaction of customers for numerous sectors. However, this will not only be a challenge for academics, but also a necessary solution for the organizations in a highly dynamic global market. The literature review focuses on three aspects related to the above, namely: 1) the transformation of logistic systems with respect to the digitalization process; 2) the role of predictive technologies and adaptive coordination mechanisms for enhancing the resilience of supply chains; 3) the role of blockchain, IoT and integrated visibility systems in supporting operational continuity and synchronisation in service system.

2.1. Digital Logistics Informatics and Service-System Transformation in Adaptive Supply Chain Ecosystems

Information technologies have become a force of fundamental change for the architecture, coordination mechanisms and the logic of the operation of global supply chains. Today's logistics environment has become a digital ecosystem within an ecosystem, in which the physical volume movement of goods is no longer the only aspect supported by digitalization, but rather digitalization of the flows of information, predictive analytics and coordinated services among the actors in the supply chain. In the era of globalization and digitalization, it is not only about optimizing the efficiency of logistics processes, but also about the resilience, adaptability and continuity of logistics processes in changing and volatile external conditions. The traditional supply chain management had a fragmented operational structure and the procurement units, warehouses, transportation departments, production planning units and distribution units were relatively independent from each other. These methods worked well when markets were stable and effective when markets were disrupted, uncertain and rapidly changing, but proved to have significant weaknesses in the former. The chain of supply logistical systems became evident to be extremely prone to cascading failures in their operations, which can rapidly spread and trigger throughout interconnected supply chains, as seen in the recent events of pandemics, geopolitical conflicts, cyberattacks, and transportation disruptions (Queiroz et al., 2019). As such, integrated logistics informatics architectures are one of the greatest strategic initiatives that modern organizations need to pursue.

Logistics informatics is the incorporation of digital technologies, operational analysis and logistics information systems into integrated logistics management environments that enable real-time decision-

making and flexible operational control. The digital ecosystems are backed by technological solutions such as enterprise resource planning systems, transportation management systems, warehouse management systems, cloud platforms and integrated communication infrastructures. These systems enable organisations to coordinate operational activities and minimise information asymmetry and speed up coordination between suppliers, manufacturers, logistics operators and retailers (Zhang et al., 2021; Saberi et al., 2019). One of the key benefits of logistics informatics systems is the ability to have real-time visibility within the supply chain operations. Digital integration enables organizations to always know how much stock is in the warehouse, where it's being transported, how well suppliers are performing, and more. All of this helps to greatly enhance managerial responsiveness to disruptions. Digital coordination mechanisms facilitated by IoT technologies and information integration systems increase transparency and enable organizations to respond better to instability in their operations (Ben-Daya, et al., 2020). Likewise, (Gu et al., 2021) have claimed that the use of information technologies positively influences supply chain performance and resilience in terms of synchronizing processes in the supply chain. Meanwhile, literature shows that technology does not necessarily lead to resilient logistics operations. Despite significant investments in digital infrastructure, many organizations are still struggling with inefficiencies in their operations. One of the main reasons is related to lack of interoperability among information systems. Many supply chains feature suppliers, manufacturers and logistics companies that employ a variety of digital interfaces with incompatible standards and disjointed communication. This means that information sharing is still limited and the effectiveness of coordinated operational response in case of disruptions is limited (Ivanov & Dolgui, 2021; Kouhizadeh et al., 2021). The other key question that must be addressed is the organizational aspect of the digital transformation. Previously published research tends to focus more on the technological aspects of the functionality, and less on aspects related to organizational adaptability, collaborative governance and organisational service coordination mechanisms. But the resilient supply chain is more than a technology issue - it's an organizational flexibility, managerial skills and inter-organizational trust one, too. Digital technologies can offer great support to the logistics operations only if adaptive capabilities are available on both the organizational level and the technological solutions themselves, regarding the ability to incorporate technological solutions into the operational and strategic decision-making processes (Papadopoulos et al., 2021; Min 2019; Al-Ababneh et al. ,2025). The service-system view has been gaining more and more importance in the recent research on logistic and service science. Value is co-created; multiple actors interact in a coordinated manner and modern supply chains are service ecosystems. Operational continuity in such systems is not only dependent on the reliability of their physical infrastructure, but also on the effectiveness of their digital communication, information sharing and synchronized managerial actions. Hence, resilience is considered a multi-dimensional phenomenon that is constructed by the interplay of technological, organizational and informational factors (Dubey et al., 2020; Prasad et al., 2021; Christopher & Peck, 2004) propose that a cloud-based logistics system can markedly enhance the flexibility and adaptiveness of supply chains in a dynamic market environment. These systems are of significant importance in international supply chains where the coordination of operations between countries and regions necessitates the exchange of data between various entities and instant managerial reactions. This means that the management of resilience has to be increasingly based on the integration of the governance of cyber security, redundant and adaptive risk management into digital logistics architectures (Spieske et al., 2021; Ponomarov & Holcomb ,2009). Another unanswered question is how the digital technologies are applied differently in various sectors and regions. For organizations in developed regions, digital integration and technological maturity are higher, while in developing regions there are financial, technological and institutional factors that may hinder the digital transformation process. This imbalance leads to significant disparities in the resilience capabilities of the global value chain and makes the development of a common set of standards on operations difficult. The existing scientific literature thus substantiates the strategic role of logistics informatics in adaptive supply chain management and reveals a lot of unsolved theoretical and practical

issues. Existing research does not fully elucidate the role of integrated digital architectures in the formation of resilience over time in the presence of complex disruptions. Furthermore, there are many approaches in analysis that are descriptive and fragmented, and they are not applicable to high levels of interconnectedness within logistics ecosystems. Therefore, the need for interdisciplinary research to integrate and combine logistics informatics with service-system theory, as well as adaptive resilience management, within the context of integrated analyses that can assess operational continuity in the presence of dynamic multi-risk environments is quite compelling.

2.2. Predictive Analytical Coordination and AI-Driven Resilience Mechanisms in Intelligent Logistics Networks

Predictive analytics and big data, along with artificial intelligence, have been significantly driving the spread of AI in the logistics sector, which has become more complex and unpredictable. There is a tremendous amount of operational information involved in logistics processes, inventory movements, supplier activities, customer needs, warehouse use and distribution network in the modern logistics business. Typical analytical methods are not effective when processing large and dynamic datasets at high speed. Due to this, the organizations are employing AI-based solutions to transform all the operational information into predictive and adaptive managerial solutions (Choi et al., 2018). One of the biggest advantages of the tools is the capability to progress SCPM from Operational Response to Disruption Prevention by predictive analytical systems. The traditional logistics management models primarily focused on the recovery of operations' viability in the event of disruption. AI-powered predictive coordination systems, on the other hand, can help companies find warning signs, predict operational risks, and simulate various situations in logistics before losses start to mount when disruptions occur. This change considerably increases the flexibility and adaptability of supply chain operations in the uncertain market (Dubey et al., 2020; Wieland & Wallenburg, 2013). Big data analytics technologies are in the middle of it. Modern logistics systems have generated data as a result of enterprise resource planning systems, the Internet of Things (IoT) sensors, customer transactions, transportation monitoring platforms and supplier databases. These data streams are processed with algorithms that recognise the activities that the ship is performing and are able to forecast the variations in demand and the probability of disruptions originating from transportation delays, stock shortage or supplier instability. (Papadopoulos et al., 2021; Zhang et al., 2021) argue that predictive analytics can improve supply chain resilience by increasing the responsiveness of logistics systems to environmental uncertainty. AI also helps in improving operational decision-making by offering machine learning algorithms that continuously learn and improve their forecasting models.

Digital twin technologies are also one more major way of predictive logistics coordination. Digital twin is a virtual representation of a supply chain physical system which enables organisations to simulate processes in the case of a disruption. Such technologies allow companies to determine the effect of transport disturbances, failures of suppliers, or even unexpected demand changes, prior to making management decisions in real operational scenarios. According to Ivanov and Dolgui (2021), a digital twin system can be utilized to significantly improve the resilience management and to support scenario-based operational planning and adaptive response strategies. Although predictive analytical systems become increasingly relevant for practice, the literature shows that there are still some leftover methodological and organizational challenges. There are many predictive models that are limited to stable operating conditions and lack the ability to adequately consider simultaneous multi-risk events that involve geopolitical instability, technology breakdown and economic uncertainty. Current analysis methods often use historical data and linear forecasting assumptions that don't necessarily capture the high volatility of operating conditions (Spieske et al., 2021; Dolgui et al., 2020). Second, there are frequent hurdles in the way of organizations making predictive analytical tools a seamless part of their digital infrastructure. Legacy ERP systems, disjointed databases, and incompatible communication solutions pose interoperability challenges and hinder the efficacy of AI-enabled coordination tools. This means that predictive systems can still deliver analytical information, even if there is no sufficient

synchronisation of the supply chain among the players. This issue becomes important with regard to the heterogeneous technological standards and decentralized governance structures in the multinational logistics ecosystems (Prasad et al., 2021). The other major issue is related to the organisational preparedness needed for the successful implementation of AI. Predictive coordination systems need to be technologically capable, as well as have very skilled workers, flexible organisations and appropriate decision-making processes. A major hurdle in the implementation of digital transformation processes is that there are employees and managers who don't have the technological skills required or who are skeptical of the analytical ways of automated systems. Hence, rather than merely implementing technology, resilience formation relies more and more on the interplay of technological innovation and organizational adaptability (Gu et al., 2021).

In the literature, it is observed that there is a shift in the current supply chain towards digital infrastructures and algorithmic decision-making processes. While AI-based systems are more accurate at predicting and preventing events, they also are vulnerable to new security risks like cyber-attacks, algorithmic flaws, and technological failures. Supply chains with a high degree of digital integration could face significant disruptions in the event of a malfunction of predictive systems or if they are attacked by cybercriminal activity. Thus, future research in resilience should focus on digital infrastructures' resilience and predictive analytics' advantages (Shoomal et al., 2024; Brandenburg 2016). Another unanswered question is ethics and governance issues around the use of AI in the logistics business. The focus of existing studies is mostly on the operational efficiency and prediction aspects of the algorithms and their capabilities, with comparatively little research on data governance and the accountability and transparency of algorithmic decisions and systems in automated logistics. In the era of growing integration of predictive technologies within operational decision-making, organisations need to have regulatory frameworks and governance models that can guarantee operational reliability, managerial control and efficiency of automation (Al-Swidi et al, 2024). Overall, this current scientific literature demonstrates that predictive analytics and AI-informed coordination processes are vital elements to greatly enhance the resilience of supply chains, both through improving the accuracy of supply chain forecasting, and by increasing the adaptability and synchrony of planning and operation in the chain. However, there are key challenges that have not been resolved yet, in terms of inter-operability, adaptation of the organization, cyber security and governance of predictive digital infrastructures. These constraints highlight the need for the creation of integrated resilience models that integrate predictive technologies, service coordination and adaptive logistics governance in dynamic environments of multiple risks.

2.3. Blockchain Traceability, IoT Visibility and Multi-Layer Service Synchronization in Resilient Supply Chains

The logistical world is increasingly insecure and this has greatly increased the need for greater transparency, traceability and coordination in supply chains to provide information sharing. Modern international value chains feature a multitude of geographically spread suppliers, manufacturers, logistics companies, transport companies, warehouses, distributors and retailers who operate in highly complex value chain networks. In such cases, a failure in one segment can very easily spread to other segments, resulting in cascading operational failures that can affect the continuity of the transportation system, the stability of the production line, availability of stock and customer service. Similarly, the value of the blockchain technologies and IoT infrastructures to improve visibility, information reliability, and coordinated resilience management of global supply chains has gained relevance (Idrissi et al., 2024; Ben-Daya et al., 2020).

Internet of Things (IoT) technologies are one of the most critical technologies in the current logistics informatics. IoT systems are comprised of sensors and tracking devices, communication channels and analytical systems that can collect and share live information about the operation of systems. Through these technologies, businesses can monitor the transportation environment, inventory movement, warehouse operations, equipment utilization, supplier activities and more in geographically distributed

logistics networks at all times. For IoT monitoring systems, organizations can easily identify deviations in their operations, identify disruptions early and take control actions to avoid a massive failure in the supply chain. IoT monitoring systems enable organisations to identify operational deviations, detect disruptions at an early stage and initiate corrective actions before local instability develops into systemic supply chain failure (Ben-Daya et al., 2020; Papadopoulos et al., 2021). The use of IoT infrastructures becomes even more evident in sectors where they can play a decisive role in the quality of the products and the continuity of services. In pharmaceutical supply chains, food logistics systems and in high value manufacturing processes, it is significant to consider environmental conditions such as temperature and humidity, handling aspects and transportation stability. Monitoring systems are known as the Internet of Things (IoT) and with the help of these systems, businesses can ensure they are in control throughout the logistics process and minimize the risk of spoilage or delays in delivery or product degradation. As discussed by (Shoomal et al., 2024), IoT could effectively improve the response of the supply chain in an unstable setting and also help to enable quicker adaptive coordination.

Another key benefit of IoT technologies is improving the synchronisation of operations among actors on the supply chain. Real-time monitoring systems help to eliminate information asymmetry and speed up communication between the various stakeholders in the supply chain, including suppliers, transport companies, warehouses and retailers. This helps the efficient control of stock, optimization and coordination of routes and disruptions. As a result, the use of IoT technologies is on the rise, not only as an operational monitoring system, but as a strategic coordination system for adaptive logistic governance (Papadopoulos et al., 2021). Incorporating blockchain technologies into IoT systems can augment the systems' capabilities by providing a decentralized and transparent digital infrastructure that facilitates secure information sharing and verification within intricate logistics environments. The blockchain systems maintain the records of their operations in distributed ledgers which are unchangeable, transparent and resistant to unauthorized alterations. These characteristics of the technology can be very beneficial in enhancing trust among the parties involved in the supply chain and also minimising risks of information manipulation, fraud and operational inconsistencies (Queiroz & Wamba, 2019).

The increased importance of blockchain technologies in resilient supply chain management is increasingly linked to the need for today's logistic chains to provide highly reliable information exchange mechanisms that are able to operate under uncertain and changing operational conditions. Blockchain traceability solutions enable businesses to track products, confirm the actions of suppliers and ensure all operations are transparent throughout several stages of the logistics chain. Blockchains can enhance resilience by enabling more accountability and less uncertainty in inter-organizational coordination processes. A key advantage of blockchain technologies is their potential to enable trust and collaborative governance in distributed logistics networks. Typically, traditional supply chains have more than one intermediary who needs to process and move the information about operations. These can lead to misaligned operations, inconsistencies and communication gaps during disruption, which can cause delays. These constraints can be overcome with the use of blockchain systems, which facilitate direct, transparent communication between the players in the supply chain without relying too heavily on the intermediaries (Idrissi et al., 2024). By combining blockchain solutions with IoT infrastructures, multi-layer visibility architectures emerge, which enable coordination of operations across global logistics systems in a synchronized way. The operational data generated from IoT devices is continuously flowing with respect to transportation conditions or the location of a product in the warehouse or its operations, while blockchain systems provide secure storage mechanisms, verification and access to the information flows. These technologies create digital ecosystems that are more transparent, have quicker information flows, and are more synchronized in operations. These systems will provide a higher level of adaptive resilience as organizations will be able to detect incidents earlier and respond more effectively, whilst ensuring continuity of logistics operations in the time of uncertainty (Al-Swidi et al., 2024).

Although blockchain and Internet of Things (IoT) technologies have great practical benefits, there are some theoretical, technological and organizational issues that have not yet been addressed in the literature. Many existing studies are mainly concerned with the technological aspects of the service while giving comparatively little attention to other aspects of service system coordination mechanisms and adaptive governance. In addition to technological visibility, however, other factors are crucial to achieve logistics ecosystem resilience: collaborative working management and/or organizational flexibility, synchronized decision-making between organizations (Gu et al., 2021). Secondly, interoperability is still one of the key challenges for successful digital integration. Different digital platforms, often with different standards, databases and communication protocols are commonly found within global supply chains, especially among organizations. However, this can make it challenging for even well-established and technologically advanced organizations to successfully adopt blockchain systems, IOT networks and ERP systems into a single ecosystem. These restrictions have a negative effect on the effectiveness of information exchange, and they also affect the capability of coordinated disruption response. The other one that remains unanswered is the scalability and economic viability of the implementation of blockchain. The benefits of blockchain technologies in terms of transparency and security are great, but there are also considerable technological investments, restructuring and adaptation of existing processes that will need to be made. The financial and technological resources are lacking in many organizations, particularly small and medium enterprises, for the implementation at a large scale. This results in the digital transformation processes across industries and geographical regions still being uneven, leading to considerable variations in resilience capacities, globally (Ivanov 2021). Rising vulnerabilities and challenges are also faced by digitally integrated logistics systems in the fields of cybersecurity and technological dependency. Though the blockchain infrastructure has high security, the IoT device and the cloud communication platforms are still susceptible to cyberattacks, unauthorized access and operational disruptions. As reliance on digital infrastructures grows, so does the risk of vulnerability in their operations, due to technical failures and cyber security threats. Resilience of the supply chain thus depends on the ability to be both operationally transparent and to have a cybersecurity governance that can defend entangled digital ecosystems both against external and internal threats (Spieske et al., 2021). Moreover, empirical studies on the long-term operation performance of large-scale blockchain and IoT systems in the case of disruption are still limited. Most of the existing studies consider pilot implementations and/or individual technological projects, but not a fully-fledged multi-national logistics ecosystem under complex multi-risk scenarios. Therefore, there is a great need for the comprehensive analysis of such aspects in coordinated service and adaptive resilience management processes in unified logistics informatics architectures that allow technological visibility. Therefore, the study formulates analytical research propositions.

P1. The integrated logistics informatics platforms have a positive effect on the operational synchronisation and the capability of adaptable recovery of the entire supply chain.

P2. Predictative coordination systems with AI decrease the chain of disruptions and increase the ability of digitalized logistics ecosystems to respond to disruptions.

P3. With the help of monitoring and traceability, which use IoT technologies, and of blockchain, the logistics visibility and trust and continuity of services increase across multi-tier supply chains.

P4. Digital integration intensity positively and significantly influences supply chain resilience performance through the mediating effect of service-system interoperability.

P5. The synergies achieved by the integration of ERP systems, predictive analytics, blockchain and IoT technology create greater resilience effects than digital solutions by themselves.

So, the literature review validates that a resilient supply chain relies on more and more integrated digital ecosystem which can facilitate transparency, predictive coordination and synchronisation of the management of the service system. However, existing research does not yet have well-established interdisciplinary models that explain how the role of ILIA in the formation of long-term resilience in dynamically-changing disruption environments. This gap is crucial to identify the need and relevance

of the present study.

3. Methodology

The importance of resilient logistics management has risen significantly as a result of the growing instability of global economic systems, increasing interdependence of logistics networks and the speed of digital transformation of supply chain operations. Today's supply chain is facing uncertainty in geopolitics, technological innovation, cyber threats, transportation issues, environmental impacts and shifts in global demand. In this context, traditional logistics management methods, which are focused mainly on minimizing operational costs and maximizing efficiency, are not sufficiently effective as they do not consider dynamic risks in operations and complex inter-organizational interdependencies (Ivanov & Dolgui, 2021; Wamba & Queiroz, 2022). The growing number of supply chain disruptions (SCD) has shown that resilience is not just about recovering when operations fail. New logistics systems need predictive coordination, adaptable operational synchronization and integrated information infrastructure with the ability to provide real-time decision making in uncertain situations. This has led to an increasing use of digital technologies by organizations as strategic tools to rapidly evolve their logistics operations and create a unified service ecosystem with a transparent service environment, coordinated operations, and adaptive responsiveness (Dubey et al., 2020). While digital transformation has become increasingly relevant in practice, current methods of assessing resilience in the supply chain have several gaps. First, a lot of empirical studies examine one technological instrument at a time, instead of studying integrated logistics informatics architectures. Second, many analytical models focus mainly on operational efficiency metrics and lack a proper consideration of service-system synchronization, interoperability and adaptive coordination mechanisms that ultimately shape the resilience performance in complex logistics ecosystems. Third, conventional quantitative assessment models often do not capture uncertainty, volatility and dynamic interactions between the technological infrastructures and operational disturbances in multi-risk contexts (Papadopoulos et al., 2021).

To tackle these limitations, the present study introduces an integrated methodological framework which is based on three principles, namely logistics informatics, service-system coordination theory and scenario-based resilience analysis. The conceptual framework of the research is formulated around the assumption that supply chain resilience can be realized as a result of the interplay between three interdependent dimensions, which are digital integration capability, operational synchronization and adaptive response capacity. It therefore examines resilience as a product of interactive performances of digital infrastructures, predictive analytical systems and logistics service coordination mechanisms. The method maintains the original research concept and analysis indicators, while integrating the original research concept with resilience modeling and service system interpretation, with the analytical depth of the study being significantly expanded by logistics informatics analysis. The tool selected for the primary analysis was scenario analysis, which allows for the performance of the supply chain to be analysed in different operational situations, which have varying levels of uncertainty and disruption. This method is particularly suitable for the modern logistics environment, where operational risks are not just linear but pervasive, and merely modeling these risks is insufficient (Al-Swidi et al., 2024).

The research methodology is divided into two analytical phases which are connected to each other. The first phase involves building an integrated logistics informatics architecture and resilience indicators that represent the digitalization, synchronization at operations and adaptive recovery capability. The second phase is a resilient modelling of the impact of digital technologies in the face of economic shocks, technological failures and combined disruption scenarios. The proposed methodological framework allows for a holistic assessment of the role of coordinated digital ecosystems in supply chain resilience in the context of existing logistics service systems.

3.1. Integrated Logistics Informatics Architecture and Construction of Resilience Evaluation Indicators

The methodological basis of the study is the concept of integrated logistics informatics architecture, which is based on the coordinated interaction of information systems, the mechanisms of operational synchronization and the adaptive decision-making processes, aimed at ensuring supply chain resilience. The present research focuses on digital transformation as a multi-layer logistics ecosystem, in which interoperability, information transparency and coordination of services are required between the various actors of the supply chain, and in turn, are a prerequisite for resilience. The suggested analytical architecture is made up of 5 interrelated operational layers: 1) Predictive Data and Operations Monitoring Layer; 2) Digital integration and digital communication layer; 3) Spotting the signs and implementing predictive analytics and scenario modelling; 4) Service coordination layer (SCL); 5) Layer of adaptive resilience response. The first layer includes enterprise resource planning systems, transportation management systems, warehouse management systems, IoT monitoring devices and supplier databases responsible for collecting operational information in real time. This layer depicts the information side of the logistics coordination as it directly affects the speed and quality of the managerial decisions made in the operation (Ben-Daya et al., 2020). The second layer is the operational data as it moves into one digital space. Information is shared between suppliers, manufacturers, logistics providers and retailers via cloud platforms, blockchain systems and interoperable communication infrastructures.

Integration quality can greatly affect operational synchronization and adaptive responsiveness in case of disturbances (Wamba & Queiroz, 2022). The third layer is the predictive analytical systems, artificial intelligence algorithms and digital twin technologies for disruption forecasting, inventory optimization and scenario modelling. The design of this layer is to enable proactive operational coordination, with the capability to execute operations under various operational conditions and discover operational weaknesses before disruptions result in systemic failures (Zhang et al., 2021). The fourth layer is the service-system coordination mechanisms which are related to the synchronization between the actors of the supply chain.

Collaborative decision making, inter-organizational communication and adaptive logistics governance are as well as technological infrastructure very important factors for continuity of operations. Therefore, the technological and organizational aspects should work hand in hand so that they can build resilience (Papadopoulos et al., 2021). The fifth layer is adaptive resilience capability, which is the ability of the organizations to keep serving, minimize recovery time, and restore operational stability, when there is uncertainty. This layer combines operational, informational and technological indicators into holistic resilience measurement systems. The study analyses how digital technologies affect supply chain resilience based on a system of integrated indicators, that are associated with the analytical logic of the original research model, but in a more detailed research method. The first indicator is the Index of Digitalization of Supply Chains (IDCSP) that evaluates the technological maturity and technology intensity of the logistics operations.

$$IDCSP_i = \frac{\sum_{j=1}^{n} w_i \cdot X_{ij}}{\sum_{j=1}^{n} w_i} \quad (1)$$

Where X_{ij} is the value of the j-th digitalization indicator for company i, w_j is the weight of the indicator determined by experts, n is the number of indicators. The IDCSP indicator includes integration with ERP, adoption of cloud infrastructure, implementation of IoT and blockchain traceability, and predictive analytics. The higher the IDCSP values, the more capable of digital integration and greater the transparency in the operations. The second indicator is the Scenario Stability Unit (SCU) that reflects the capacity of supply chains to remain stable during disruption.

$$SCU_i = \frac{RTO_{base}}{RTO_{scen}} \quad (2)$$

Where RTO_{base} is the baseline supply chain recovery time, RTO_{scen} is the recovery time under a specific risk scenario. SCU > 1 indicates increased resilience due to the use of IT. A score higher than

1 means greater resilience and quicker adaptive recovery. The third indicator is the Index of Supply Chain Adaptability (IACP), which reflects the efficiency of logistics to reduce the time required for reacting to changes in the system following digital transformation.

$$IACP_i = \frac{LT_{avg} - LT_{IT}}{LT_{avg}} * 100\% \quad (3)$$

Where LT_{avg} - average delivery time before IT implementation, LT_{IT} - after implementation. This index reflects the ability of the supply chain to reduce the response time to external changes. More integrated resilience indicators were added to enhance the analytical depth of a study.

The Integrated Logistics Resilience Index (ILRI): Evaluates the logistics operational resilience performance:

$$\mathrm{ILRI_i} = \sum_{j=1}^{n} w_j \cdot D_{ij} \quad (4)$$

Where D_{ij} - resilience component value; w_j – weighting coefficient of resilience factor. The Service Coordination Stability coefficient (SCS) measures synchronization intensity between logistics actors:

$$SCS_i = \frac{IS_i + TR_i + CI_i}{3} \quad (5)$$

Where IS_i - information synchronization level; TR_i - transparency ratio; CI_i – coordination intensity. The Adaptive Logistics Synchronization Coefficient (ALSC) evaluates operational synchronization efficiency during disruptions:

$$ALSC_i = \frac{OC_i}{DT_i} \cdot 100 \quad (6)$$

Where OC_i – operational coordination capability; DT_i – disruption time duration. The empirical database of the study includes multinational companies representing logistics-intensive industries characterized by different levels of digital maturity and operational integration. A purposive comparative case-selection strategy was used to create the empirical sample.

The selection of five multinational companies was based on their involvement in logistics-intensive industries, varying degrees of supply chain digitalization, exposure to global operations and complexity of the service system. These are high value technology supply chains, manufacturing and automotive logistics, consumer goods distribution, global logistics services and retail and omnichannel logistics, respectively, represented by the companies Apple, Toyota, Unilever, DHL, and Walmart. The purpose of the sample is not the statistical generalisation but to facilitate analytical comparison of digitally enabled resilience patterns at different logistics service systems that are more heterogeneous.

The indicators in Table 1 have been created using a structured scoring process derived from publicly published annual reports, sustainability reports, logistics reports, digital transformation reports and descriptions of operations. All indicators were standardised to a similar scale. Digitalization level was evaluated by looking for ERP integration, cloud platforms, IoT visibility, blockchain traceability and predictive analytics. The 1-5 coding system for IT integration was based on the digitization of logistics, ranging from 1 (fragmented digital tools) to 5 (integrated logistics informatics architecture). Qualitative factors were coded based on specific criteria - low, medium, high and very high - for factors like predictive capability and service continuity. The operational indicators were derived from annual and integrated reports published by Apple, Toyota, DHL, Walmart and Unilever for 2023–2024.

Table 1. Initial indicators for scenario analysis of IT-enabled supply chain resilience in global logistics operations

Company	RTO (hrs)	LT (days)	Digitalization Level (%)	IT Integration (1 - 5)	Outages per Year	Predictive Capability	Service Continuity Level
Apple	72	7	85	5	3	High	High
Toyota	96	10	78	4	5	Medium	Medium
Unilever	60	8	65	3	4	Medium	Medium
DHL	48	5	92	5	2	Very High	Very High
Walmart	72	6	88	5	3	High	High

The operational indicators were derived from annual and integrated reports published by Apple, Toyota, DHL, Walmart and Unilever for 2023–2024.

The selected indicators provide a full set of analytical metrics to evaluate the effects of digital integration on operational support synchronization and adaptive coordination and resilience in uncertain logistics conditions.

3.2. Scenario-Based Modelling of Adaptive Supply Chain Resilience under Multi-Risk Operational Conditions

The second phase of the methodological framework is a resilience modelling based on scenarios to determine the operational impact of digital integration in dynamically evolving disruption environments. Consequently, scenario analysis was chosen based on the conditions of the contemporary supply chains, which are high in uncertainty and have changing operational risk and high interdependency between technological and organizational systems. In such environments, the traditional static forecasts models often don't account for the complexity, while scenario analysis allows for the analysis of a number of alternative operational conditions and adaptive response mechanisms (Ivanov & Dolgui, 2021).

The methodological framework of the present study takes as a premise that digital integration capability, combined with the operational disruption, and adaptive coordination mechanisms constitute the basis of the resilience performance. Hence, the study not only assesses the operational results but also the capacity of logistics systems for providing continuity of service and synchronized decision making in the case of uncertainty. Three main disruption scenarios were created to represent the three key forms of operational instabilities in today's global supply chains. The first one is an economic shock environment. This scenario encompasses quick drops in demand, supplier volatility, transportation price volatility and disruption due to geopolitical uncertainty. Modelling assumptions involve a 20% drop in demand, longer supplier lead times, longer transport times and partial disruptions to procurement processes. This scenario is analogous to the conditions that are often found in the midst of an economic crisis, inflationary instability and trade restrictions (Wieland 2021). The second scenario is considered as a case of technological disruption due to failure of operational information systems and digital infrastructures. This scenario involves temporary ERP system unavailability, disruption of cloud communication platforms, fallout of IoT monitoring and loss of data synchronization. It is assumed that the operational information integration will be reduced by 20% and that the predictive analytical systems will be disrupted for 48 hours. These scenarios mimic cybersecurity attack scenarios, failures in technology, and the instability of digital infrastructure that is becoming commonplace in modern logistics operations (Spieske et al., 2021). The third case scenario is the integrated disruption, in which both the economy is unstable and technologies fail. This is an extreme situation where organisations are faced with multiple disruptions by their suppliers, at the same time as demand changes, and digital coordination systems are delayed or interrupted. Combined disruption modelling is especially relevant here, as in the modern supply chain, crises often consist of several operational risks interacting as a chain that cause the failure.

Table 2. Scenario-based resilience evaluation of digitally integrated supply chains

Company	SCU Scenario 1	SCU Scenario 2	SCU Scenario 3	ILRI	ALSC (%)
Apple	2.8	2.5	2.2	0.88	81
Toyota	2.1	1.9	1.6	0.74	68
Unilever	2.3	2.0	1.8	0.71	65
DHL	3.9	3.5	3.2	0.95	92
Walmart	3.1	2.8	2.4	0.91	87

Source: Authors' calculations based on scenario modelling from annual and integrated reports published by Apple, Toyota, DHL, Walmart and Unilever for 2023–2024.

The results suggest that the extent of digital integration is positively related to the extent of the operational synchronization of companies as well as their resilience even in the event of disruption. The assumptions adopted with regard to the scenario parameters are not predictions but rather moderate stress-test parameters. The 20% demand drop is a moderate severity economic shock event, enough to impact procurement and inventory planning, and transportation capacity, but not necessarily a complete market failure.

The 48-hour ERP/cloud-platform outage is one that affects operations, may impact order processing, data synchronisation and logistics coordination, and will be short-term. To mitigate reliance on any one assumption, a sensitivity check was included and conducted by comparing moderate, severe and extreme disruption levels.

Table 3. Sensitivity analysis of disruption assumptions

Scenario level	Demand drop	Digital outage	Expected effect
Moderate	10%	24 hours	Limited instability
Baseline	20%	48 hours	Noticeable operational disruption
Severe	30%	72 hours	High recovery pressure
Extreme	40%	96 hours	Systemic resilience stress

DHL and Walmart show the highest resilience performance out of all the logistics chains studied because they possess interoperable logistics systems, a higher predictive coordination capacity and they have a higher degree of integration of digital infrastructures. On the other hand, organizations with low integration intensity are found to have low adaptive recovery performance and long operational stabilization period.

The modelling results also show that the resilience effects of isolated technological implementation are far less than the integrated digital ecosystems. organizations that are adopting ERP systems, IoT monitoring infrastructures, predictive analytics, blockchain traceability and cloud coordination platforms all at once, are more likely to exhibit adaptive synchronization and quicker recovery ability.

The analysis proves that Digitally Integrated Supply Chains (DISCs) possess the features of better synchronization of operations, less propagation of disruption, and greater stability of service continuity in uncertain conditions. Thus, resilience is increasingly reliant on the ability to support predictive coordination and adaptive governance in integrated logistics informatics architectures, which are capable of operating in multiple, interdependent logistics ecosystems (Sharma et al., 2020).

The results confirm that the assumption of the development of the service system's coordination is the prerequisite for the development of resilience, not the technological functionality itself. To further increase the reliability of the study, operational synchronization evaluation and service continuity analysis were also included in the scenarios.

Table 4. Operational synchronization and service-system coordination under disruption scenarios

Indicator	High Digital Integration	Medium Digital Integration	Low Digital Integration
Recovery Speed	Very High	Medium	Low
Information Transparency	Very High	Medium	Low
Predictive Coordination	High	Medium	Weak
Service Continuity	Stable	Partially Stable	Unstable
Disruption Propagation	Limited	Moderate	High

The methodological framework thus proves that the scenario-based resilience modelling is an effective analytical tool for analysing the effects of digital transformation on global logistics operations. The use of resilience indicators, service-system coordination analysis and modelling of disruptions significantly improves the methodological depth of the study and allows for the comprehensive evaluation of the adaptive formation of resilience in today's digitally integrated supply chains.

4. Empirical Results and Interpretation

International supply chains are one of the key factors in determining an organization's competitiveness in the face of growing geopolitical volatility, tech upheavals and the fast pace of digitalization of economic systems. Modern logistics are highly interdependent, have informational complexity and cross-border coordination: all these make logistics ecosystems highly vulnerable to external shocks. In this case, logistics operations are gaining in efficiency and effectiveness according to the transport capacities, as well as in terms of digital coordination of actions, their adaptability to changes, and the continuity of services in the event of a disruption (Ivanov & Dolgui, 2021). The methodological analysis conducted showed that the phenomenon of resilience in modern supply chains can be understood as a multidimensional one that is created by the interaction of technological integration, predictive coordination and synchronization of service systems. The empirical results acquired are confirmatory of the degree of impact that digital transformation has on the continuity of operations and adaptive recovery capability of logistics ecosystems. The resilience performance of organisations with a higher level of digital integration is significantly higher in the event of an economic shock, technology failure and combined disruption. The outcomes confirm the findings of the earlier studies that have been conducted on the development of strategic position of logistics informatics and predictive digital infrastructures in adaptive supply chain management (Dubey et al., 2020; Baryannis et al. 2019). In addition, the scenario analysis indicates that effects on resilience cannot be optimised if tools from the area of technology are used without others. Technologically holistic organisations for digital ecosystems, ERP, IoT monitoring and predictive analytics, blockchain traceability and cloud coordination infrastructures are the most operationally consistent businesses. These systems involve information sharing, and the dissemination of disruption reduction and enhancement of adaptive operational coordination by the chain actors. The flexibility and responsiveness is now more related to interoperability and integrated logistics governance, rather than merely technological ones (Papadopoulos et al., 2021).

The empirical modelling also shows that the continuity of the services while operating is a crucial factor in a service system's coordination. In the face of disruption, more inter-organizational synchronisation and digital interoperability are linked to higher levels of adaptive responsiveness, and to faster logistics operation recovery processes. The findings are a significant extension of the traditional resilience theory as it shows that coordination of information sharing and synchronisation of digital decision making in inter-connected logistics networks is another crucial factor that gives rise to resilience (Gu et al., 2021). In the next subsections, the empirical analysis of the analysis of scenario-based resilience modelling and integrated logistics informatics performance for various operational disruption cases is presented.

4.1. Scenario-Based Adaptive Resilience Modelling and Integrated Logistics Informatics Performance under Multi-Risk Operational Conditions

The analysis carried out in the scenario shows that the level of digital integration and the operational synchronisation and predictive coordination capability have a significant impact on the resilience of modern supply chains. The results of the empirical modelling confirm the proposition that in situations of economic instability, technology disruption and combined operational shocks, Digital Integrated Logistics (DIL) ecosystem factors of adaptive response capacity are significantly higher. The result is of importance as modern supply chains face multi-risk situations that are not just a series of risks that

happen one after the other. The first part of the empirical analysis was to evaluate the impact of IDI on adaptive capacity to economic shocks. The modelling assumptions were demanding reduction, supplier unreliability, transportation lead time and variations in procurement operations. The results show that there are significant variations in levels of resilience between organizations with varying degrees of digital integration. The modelling results also indicate that coordination early in supply chain based on predictive analytics played a key role in minimizing the propagation of disruption in a digitally-integrated supply chain. Similar findings regarding predictive analytics and digitally enabled supply chain resilience were identified in prior studies on data-driven logistics ecosystems (Wamba et al., 2020). Businesses used AI-driven forecasting tools to identify deviations in operations early on and modify their transportation schedules, inventory management and supplier coordination processes as a result. The recovery time was greatly shortened and the losses of the unstable suppliers and transportation interruption were minimised with operational synchronisation which adjusted to the process of production (Choi et al., 2018).

As described in this dynamics, digital transformation has moved from being an option for operational innovation to a strategic need. Growth was especially noteworthy in the infrastructure for IoT, in predictive analytics systems, and in cloud coordination platforms, which directly impact the visibility of operations and adaptive coordination ability. Conforming with the earlier research, which highlighted the increasing relevance of integrated digital ecosystems in the context of resilient logistics operations (Ben-Daya et al., 2020), these results are similar.

Empirically, the results suggest that, at the same time, the less interoperable organizations, and the ones with very fragmented digital infrastructures, had a much poorer resilience performance. Adaptive synchronization indicators were not observed as much on Toyota and Unilever, due to limited integration of the coordination mechanism with predictions, and fairly weak operational visibility mechanisms. These organisations have adopted some digital technologies, but have faced challenges of not being synchronised between the operating platforms impacting on processes for responding to disruptions and recovery times during economic instability.

The dynamics of digital logistics informatics for supply chain ecosystems around the world is shown in figure 1 from 2020 to 2025. The statistical analysis reveals consistent adoption of ERP across different industries, warehouse automation technologies, IoT implementation/ adoption and blockchain in the industries.

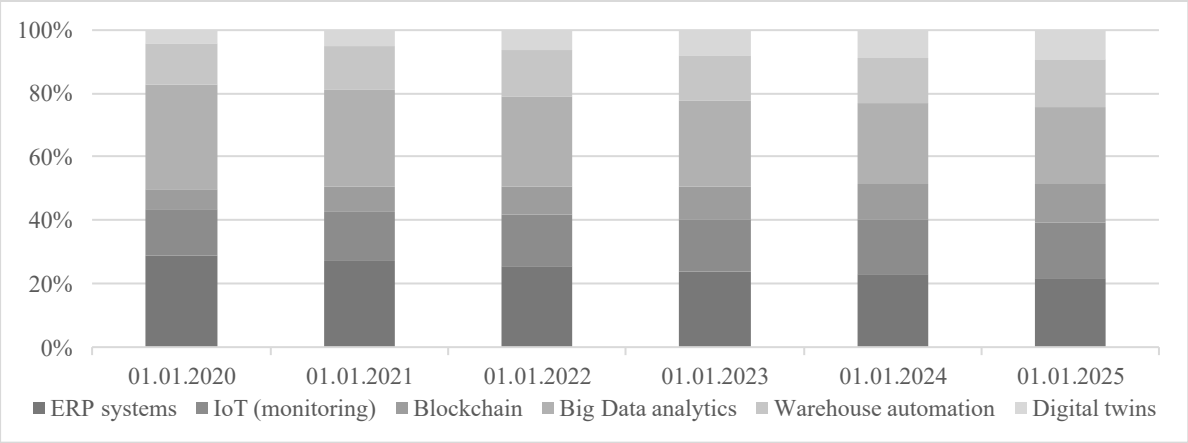


Fig.1: Global trends in terms of the share of companies using key IT technologies in global supply chains for the period from 01.01.2020 to 01.01.2025, %

Source: Authors' research from annual and integrated reports published by Apple, Toyota, DHL, Walmart and Unilever for 2023–2024.

The findings derived show a strong support for the support Proposition P1, that Integrated logistics informatics platforms have a positive effect on operational synchronisation and adaptive recovery capability of global supply chains. Companies that had a more integrated digital platform had much

more operational continuity and speed of stabilisation than those with disjointed technology. The other major component of the empirical analysis will be technological disruptions that might occur in the event of failure of digital infrastructures, disruption of cloud communications systems and restrictions on the availability of operational data. The modelling assumption included temporary ERP coordination systems disruption, reduced information synchronisation capability and temporary inaccessibility of predictive analytical platforms for 48 hours. The results obtained show that digital infrastructure instability risk is still present in organizations with a high operational coordination ability. Companies with more interoperability and digital redundant companies were significantly less willing than the less interoperable and centralized companies. The logistics systems were also designed on top of redundant cloud infrastructures, distributed operational coordination mechanisms and adaptive synchronization protocols, thus ensuring the continuity of the activities of DHL's logistics infrastructure in case of temporary digital failure, and exhibiting the greatest technological resilience. The analysis also shows that the trust in the system and the spread of the disruption can be significantly reduced in the case of a technology failure, if the coordination system is based on blockchain. Lower rates of information exchange because of decentralized nature of digital ledgers, leading to lower coordination instability for organisations with blockchain traceability infrastructures. The results are aligned with the research that helped in the development of Proposition P3: Blockchain traceability and IoT monitoring positively influences logistics visibility and service continuity in interconnections supply chain systems (Wamba & Queiroz, 2022). As seen in Figure 2, there are some patterns with regard to the implementation of the logistics informatics architectures in the sectors that are both country and industry specific.

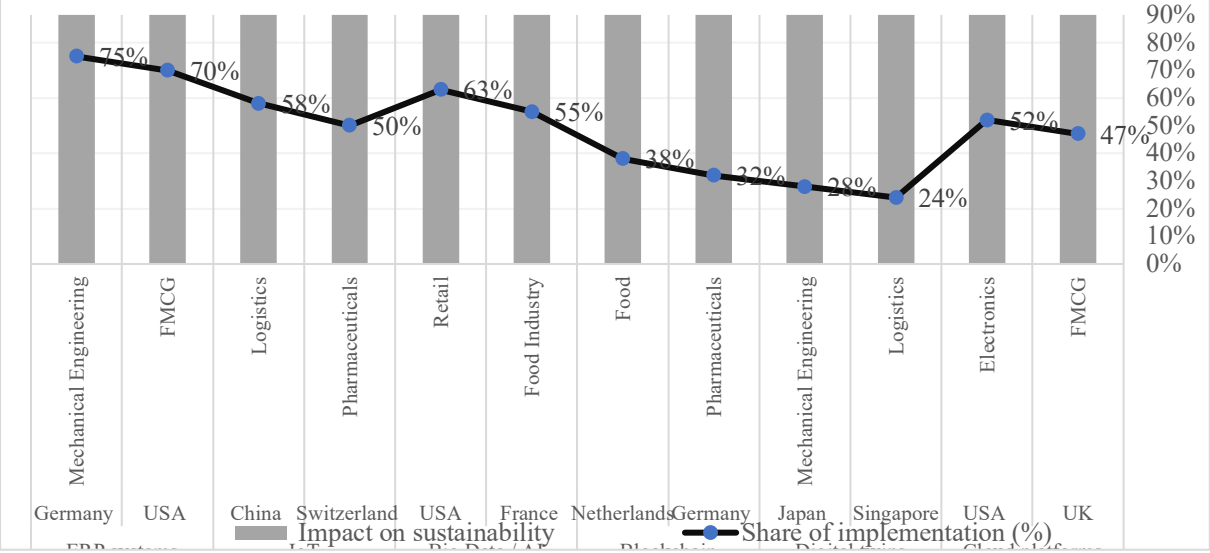


Fig. 2: Cross-sectoral implementation of resilient logistics informatics architectures by country and industry

Source: Authors' research from annual and integrated reports published by Apple, Toyota, DHL, Walmart and Unilever for 2023–2024.

Comparative analysis shows that there are also considerable differences in digital maturity and resilience capability of industry and geographical regions. Germany, the United States, and China have the most advanced ERP integration and cloud infrastructure implementation, while China is seeing the most rapid expansion in IoT-enabled logistics systems. The countries where the use of these block chaining coordination technologies is highest are Switzerland and the Netherlands. The performance of resilience varies widely by region, in part because there is no operational synchronisation capability and reliance on standards of digital integration and interoperability in logistics ecosystems. The key finding is the synergy that is achieved through integrated digital ecosystems. When it comes to ERP technologies such as predictive analytics, blockchain traceability and IoT monitoring and digital twin simulation, it's companies that are incorporating all three that were more resilient. Together these

technologies increased the transparency of operations, decreased time to disrupt operations and increased adaptive coordination capacity in uncertain environments. The findings clearly support the Proposition P5 that the synergies arising from an integration of ERP systems, predictive analytics, blockchain and IoT technologies significantly increase the resilience effects compared to technologies alone.

The results further validate that the development of resilience is achieved by a coordinated collaboration within service systems, but not by independent optimization mechanisms within the service systems. The empirical analysis also reveals that the level of digital integration is significant with regard to the intensity of the spread of disruptions. There were cascading operational failures where organizations had poor operational synchronization as a result of having weak communication systems that made it harder for managers to respond and less transparent to get operational information. In contrast, real-time information sharing and predictive coordination mechanisms (Papadopoulos et al., 2021) were used to minimise the propagation of disruption in ILS. With the scenario-based Digital integration in the supply chain adaptive resilience performance, as illustrated in figure 3, the broader context of the supply chain is considered.

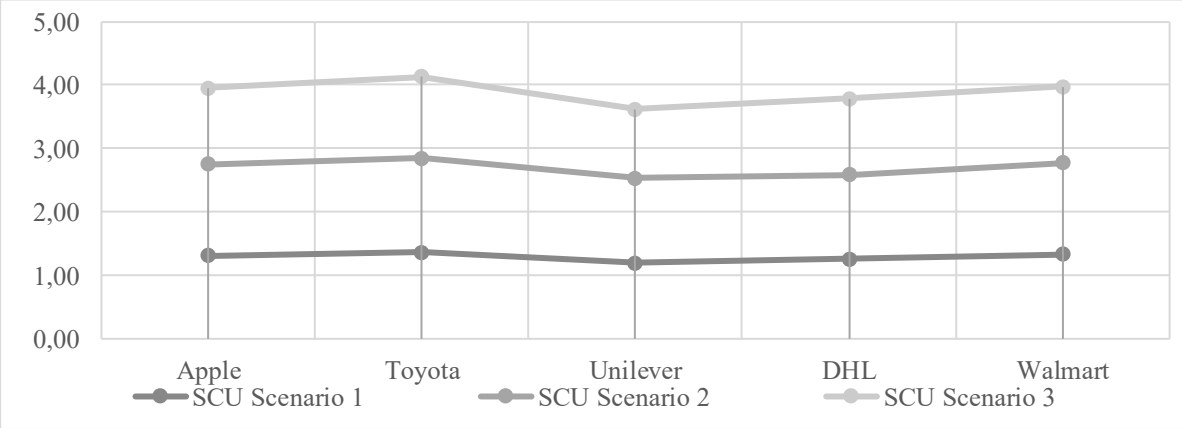


Fig. 3: Scenario-based adaptive resilience performance across digitally integrated supply chains
Source: Authors' research from annual and integrated reports published by Apple, Toyota, DHL, Walmart and Unilever for 2023–2024.

The results reveal that there is a clear correlation between a digitally mature organisation and its operations continuity in all disruption scenarios. The logistics' predictive coordination capability and the service-system coordination and digital visibility were the top two factors that led to the best resilience performance, as shown by DHL and Walmart. This includes the need for digital interoperability and coordination in logistics for the establishment of adaptive resilience. Therefore, the scenario modeling validates the reality of integrated logistics informatics architecture (ILIA) having the capability of providing predictive coordination, synchronized operational management and adaptable service continuity in the presence of uncertainties during operations, is gaining more importance in today's supply chains as the key enabler for resiliency.

4.2. Service-System Synchronization, Predictive Coordination and Intelligent Logistics Governance in Digitally Integrated Supply Chains

The second part of the empirical analysis was to test the relationship between the predictive coordination and the intelligent logistics governance and the above-mentioned relationship between the service-system synchronization and the above. The outcomes achieved demonstrate that the exchange of information, inter-organizational coordination and synchronized decision-making between the supply chain actors is a critical factor for achieving operation resilience – which is gaining relevance more than ever. In fact, resilience needs to be defined not only as a technological function but also as the outcome of the coordinated cooperation between digital infrastructures and organizational adaptability and

logistics governance of the collaboration process (Gu et al., 2021). The relevance of predictive analytical systems which can be used to reduce the propagation of disruption and synchronizing operations adaptively is one of the most important findings of the empirical study. Those companies that leveraged AI-powered forecasting tools had significantly improved ability to respond to operations during turbulent times. Predictive analytical tools that could foresee changes in demand, shipping delays and supply issues ensured that companies were not caught up in operational issues or institutional problems. Under such predictive coordination, the uncertainties of the operating conditions, inventory allocation, and transportation planning and coordination were dramatically improved. The empirical modelling proves that the predictive coordination mechanisms gives significant reduction in recovery time and better continuity of logistics operations. Companies that adopted the analytical systems based on AI and incorporated them into their processes benefited from faster operations stabilization because their predictive models enabled them to take proactive decisions rather than reactive measures to recover operations. This result is consistent with Proposition P2 - AI systems for predictive coordination have a positive effect on the responsiveness of resilience in digitally integrated logistics ecosystems (Zhang et al., 2021). A second empirical finding is that the process of resilience building must be transparent and incorporate interoperability between services. Integrated communication platforms improve the synchronisation of information between logistics actors in disruptions and were observed to have a significant impact on the capacity of organisations to coordinate their actions in disruptions when they had more digital interoperability. Under the unpredictable circumstances, cloud infrastructures enabled real-time information exchange, blockchain coordination systems accelerated adaptive operational responses and IoT monitoring platforms enabled the monitoring.

The analysis also reveals that the capacity to ensure continuity is also very reliant on the level of intergovernmentalism in the supply chains. Resilient performance was significantly higher in organizations that were characterized as having high levels of inter-organizational trust and communication systems than in those that had low levels of inter-organizational trust and communication systems. The findings are in line with the previous studies that highlighted how collaborative service ecosystems are crucial for the evolution of resilience - not only due to the optimization of individual operational elements (Papadopoulos et al., 2021). The impact of the digital informatics infrastructure on logistics resilience sustainability is illustrated in figure 4.

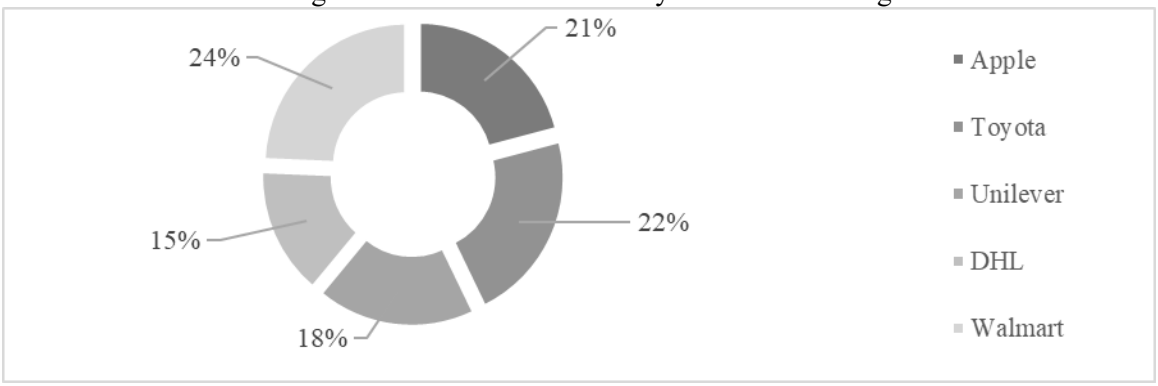


Fig. 4: Integrated influence of digital informatics infrastructure on logistics resilience sustainability
Source: Authors' research from annual and integrated reports published by Apple, Toyota, DHL, Walmart and Unilever for 2023–2024.

As indicated in the figure, organizations with highly integrated logistics informatics architecture are much more resilient in terms of sustainability than the organizations with fragmented technological architectures. Predictive coordination, cloud-based systems synchronization, IoT visibility, and blockchain traceability are seen as the most integral forms of resilience influence within Walmart and DHL's operational systems that are integrated into a digital ecosystem. The results of the empirical analysis also indicate that the effect of the level of digital integration intensity on digital resilience performance is through the mediation of digital service-system interoperability. The groups with high

level of technological infrastructure and a low level of coordination had relatively low level of resilience, and the groups with a high level of technological infrastructure and collaborative governance mechanisms had relatively high level of resilience. The results support strongly Proposition P4 which suggests that service-system interoperability can be considered as a mediator in the process of building resilience. Another important result is that digital synchronization has an effect on the intensity of the disruption propagation. Poor organizational communication coordination resulted in high levels of instability which were caused by fragmented digital infrastructure, making it difficult to recognise a disruption and limiting operations' response. However, disruption propagation was mitigated in the integrated logistics ecosystems by the coordinated managerial action and coordinated information sharing (Dubey et al., 2020).

The empirical modelling also reveals that there are large differences between the types of resilience-building processes in the various sectors. More complex industries, such as logistics, were more likely to have predictive analytical systems, or IoT visibility infrastructures. More logistics-based industries have been identified as being more dependent on predictive analytical systems and IoT visibility infrastructures. The pharmaceutical and food industry chains were particularly well served by traceability systems that include blockchain; the continuity of their services and the reliability and security of their products were closely related to transparency. The retail sector and transportation industry were found to be more dependent on AI-driven tools and systems for cloud coordination and forecasting systems due to the dynamic nature of demand and logistics requirements in these sectors (Ben-Daya et al., 2020). The other important finding has to do with the development of intelligent logistics governance as one of the strategic approaches to the adaptive development of resilience. It is found that there is a need to create a more unified governance system in order to coordinate technological infrastructures, synchronize operations and make managerial decisions adaptively in the organizations. As logistics networks are more and more interconnected and operating conditions are growing more complex, and the digital infrastructures of logistics networks are becoming more decentralized, traditional hierarchical management schemes are proved to be ineffective. The empirical results also reveal that cybersecurity and digital infrastructure stability are emerging relevant risk factors for resilience. Technological disruption scenarios applied to organizations that had high levels of technological integration and low levels of cybersecurity governance. High levels of cybersecurity governance among organizations and low levels of technological integration were correlated with technological disruption scenarios. Therefore, integrated digital governance strategies must be developed, including considering predictive analytics, as well as operational synchronisation and coordination of cybersecurity in logistics synchronised informatics architectures (Spieske et al., 2021).

Further, the analysis reveals that the continuous digital adaptation (assuming no technology implementation) is the basis for performance of resilience now more than ever. Organizations that had flexible digital systems and operational coordination that was flexible had a higher degree of long-term resilience than those with rigid operational systems. They are congruent with the idea that to grasp resilience as an ability, it requires a continuous process of technological learning, of organisational adaptation and of coordinated digital transformation. The overall findings from the empirical analysis show that logistical ecosystems that are digitally integrated do have a significant effect on the adaptive resilience capability by enacting coordination in advance, synchronizing operational processes in and between the logistics partners, and by cooperatively governing the service systems. The results show that in today's supply chains, being resilient relies on a combination of operational visibility, predictive analytics, adaptive synchronization, and intelligent governance mechanisms that are integrated into a digital ecosystem.

5. Discussion

The empirical analysis performed here, shows that the current Supply Chains' resilience relies more and more on the quality of the digital integration, operational synchrony and adaptive service-system

coordination. Concurrently, the empirical results bring to light some key managerial and methodological implications. Digital technologies can have a strong impact on making operations more transparent and coordinating operations ahead, but to a high degree depending on the level of interoperability and the security governance and readiness for adaptive digital changes. Therefore, future strategies for resilience should not be limited to technological aspects, but should also encompass logistics governance, joint management of operations and coordinated and synchronized service system management in global supply chains.

5.1. Theoretical Reconfiguration of Supply Chain Resilience through Integrated Logistics Informatics and Adaptive Service-System Coordination

The results of research are significant and provide an additional perspective – the integrated logistics informatics and service-system – in the study of the supply chain resilience, which is different from operational viewpoints. Traditionally, logistics stability has been concerned with the operational flexibility, inventory redundancy, supplier diversification and recovery speed. Prior to this, operational flexibility, stock redundancy, diversification of suppliers and recovery speed have been the major topics for research in logistics stability. Empirical results from the present study reveal, however, that resilience is becoming progressively realised as a consequence of coordinated interactions between digital infrastructures and predictive analytical systems and synchronised operational governance processes. One of the most important theoretical implications is the transition from the "supply chain to digitally connected service ecosystems" which is central to the issue. Modern logistics operations are not a physical distribution system anymore, but rather a system of information, a continuity of operations depending on the capacity of communicating synchronously, of being visible at any time, on being predictable of what's going to happen. Therefore, the study confirms the relevance of logistics informatics as a part of the adaptive resilience of the system and as a technological auxiliary tool is not. The results also showed digital interoperability and operational synchronisation to have a great influence on the development of resilience. Companies that had ERP, predictive analytics, IoT monitoring and blockchain collaboration strategies as an integrated solution were consistently out-performing in resilience testing scenarios. The results demonstrate that the quality of digital integration is a more important aspect of resilience than the use of individual digital tools. The results of such studies are especially relevant because the majority of the previous studies have focused on technological efficiency issues and relatively ignored the coordination issues of the service system as well as the issues of collaborative operational governance (Dubey et al., 2020). Another important theoretical contribution is on the concept of predictive coordination of adaptive logistics ecosystems. The supply chain models that were common were reacting to the instability of the supply chain which were used in a reactive operational management. The findings of this study, however, indicate that a disruption anticipation capability, operational synchronization and adaptability can be greatly improved through AI's ability to deliver this type of predictive analytics. From this perspective, predictive coordination is a paradigm that transforms the concept of resilience from a reactive recovery process to an organisational capacity which builds on ongoing monitoring, predicting and coordinating managerial reactions.

The outcomes are also a reflection of the service-system dynamics of the formation of resilience. Supplier, manufacturer, logistics companies and digital coordination platforms are starting to play a crucial role in supply chain sustainability. Therefore, resilience has to be interpreted as an emergent attribute that emerges during the coordinated interactions that can take place among services of interdependent logistics ecosystems, and as an organizational capability (Papadopoulos et al., 2021). Furthermore, the study indicates the growing significance of the integrated digital governance concept in the field of resilience theory. Recent approaches to resilience do not emphasize the importance of interoperability and cybersecurity coordination and collaborative information sharing to operational continuity. However, the empirical findings demonstrate that even the “high-tech” are vulnerable in

particular in fragmented or unsynchronized digital infrastructures. Therefore, the concepts of governance structures, interoperability mechanisms and a flexible digital management are relevant dimensions for further theoretical modelling of supply chain resilience. Results also show that the process of developing resilience is very dynamic and context dependent. But the role of digital infrastructures is very much determined by the nature of the industry, the level of technological evolution and the flexibility of the organization, as well as the severity of external shocks. Therefore, it is necessary to create and test universal resilience models which have a limited explanatory power in the context of highly volatile logistics environments. Future theoretical advances should focus on flexible and scenario-based models of resilience that are able to include the dynamic relationships between technological, organizational and environmental aspects of global supply chains.

5.2. Predictive Coordination, Digital Interoperability and Intelligent Governance as Determinants of Operational Continuity in Global Logistics Ecosystems

The empirical results show that predictive coordination and digital interoperability are becoming more and more decisive for the continuity and stability of the logistics operations in globally connected value chains. The study results are especially relevant to adaptive operational synchronisation and disruption management, where AI-driven analytical systems have a positive impact. The resilience of organizations in terms of their performance and quick recovery was significantly higher in the case of economic disruption, but in the case of technological disruption, it was significantly higher in terms of performance but not in terms of quick recovery. The findings and results presented above show that predictive analytics can enable logistics management to move to a more proactive level of operational response from logistics and coordination, and disruption prevention. Operational data linked to transportation movements, supplier operations, inventory changes, and customer demand are constantly fed into artificial intelligence systems. Consequently, organisations can identify and address weaknesses in their activities before they are a significant, large-scale failure. Under unstable market conditions, this predicting ability can greatly enhance the efficiency of transportation planning, inventory allocation and supplier synchronization (Zhang et al., 2021). The second implication is about the ability to interoperate with digital systems and the implications for resilient logistics governance. Although tech investment in the organisations is high, the analysis reveals that the organisations with disjointed digital infrastructures have low operational continuity. Logistics coordination mechanisms, communication platforms and analytical systems were not well integrated, leading to operational instability. So if the only focus of a digital transformation plan is on the technology, with no guarantee of interoperability, it can have only partial impact on resilience. The study also confirms the strategic importance of the cloud infrastructures, coordination systems on the blockchain and coordinated systems of information sharing. Improved real-time communication among suppliers, logistics providers and retailers, which resulted in a lower risk of disruptions being propagated and better collaboration in operational decision making. The extent of this coordination became even more relevant when taking into consideration the failures of technology, and also in the face of disruptions in transportation where the adaptive response was carried out in time, affecting the continuity of service (Wamba & Queiroz, 2022). The second big factor that's worth stressing with regards to intelligent governance is the necessity for adaptive resilience formation. Organizations with flexible operational coordination and collaborative management model were more responsive to uncertainty than organizations with rigid hierarchical management model. As a result, resilience relies more and more on the capacity to implement governance arrangements which are decentralised and adaptive, and can facilitate coordinated managerial reactions in complex logistics ecosystems.

Furthermore, the empirical results indicate that in future there should be a stronger linkage between the management of resilience and the governance of cyber security in logistics informatics architectures. Digital transformation is not only improving the visibility and predictive coordination of operations, but also increasing technology dependency on technologies that can be vulnerable to cyber-attacks and

operational failures. So coordinated cybersecurity protection needs to be a crucial element in long-term resilience strategies, as well as digital redundancy and governance of technological adaptation.

5.3. Strategic Implications for Future Development of Resilient Logistics Ecosystems under Conditions of Digital Transformation and Global Operational Uncertainty

The results of the study provide valuable strategic guidance for future development of resilient logistics systems in uncertain contexts with increasing digitalization. Among the main conclusions, the capacity to be resilient has become a central ability of an organisation that is playing a direct role in the sustainability of operations, continuity of services and competitiveness in global markets. Hence, digital transformation needs to be thought of as a holistic restructuring of logistics coordination and governance of services, rather than a technological solution. The study reveals that future supply chains will increasingly be supported by integrated logistics informatics architectures that will integrate predictive analytics, blockchain traceability, IoT visibility and cloud coordination into one digital supply chain. They increase the transparency of the operation, synchronize the operation adaptively and greatly reduce the propagation of disturbances in unstable operation conditions (Ben-Daya et al., 2020; Wamba et al., 2020). Thus, there is a need for organisations to take a more strategic approach to interoperability of digital systems, rather than a fragmented approach to technology solutions for sustainable resilience. The other significant implication has to do with the need for greater collaboration among actors in the supply chain across supply chain ecosystems. The study reveals that a growing role of inter-organizational trust and coordinated decision-making process by logistics operators, supplier and retailer and the same time the synchronized information sharing process between the actors becomes more significant for resilience. The logistics system in the future should thus be even more decentralized and flexible in terms of governance to enable rapid coordination of logistics operations in an uncertain and changing context.

The results also highlight the increasing relevance of predictive Resilience Management. Systems that plan for a fixed state are not working in this geopolitical environment with the cyber risk and very dynamic demand. In contrast, predictive analytical systems, and digital twin technologies, greatly enhance disruption anticipation and adaptive operation coordination. Therefore, there is a need to invest more and more in AI-based forecasting systems and scenario-based resilience modelling infrastructures (Papadopoulos et al., 2021). Finally, it confirms the resilience as a continuous strategic process, that requires constant adaptation to the process of digitalization, operational learning and co-creating governance. Predictive coordination, collaborative management and interoperable digital infrastructures will contribute to organizations being much more adaptive and have an increased long-term competitiveness in highly volatile global logistics. There are some limitations of the study. It is an empirical design that does not attempt statistical generalisation, but rather comparative scenario modelling. Secondly, indicators at the company level are based on a combination of publically available reports and a company scoring system; hence results are approximate analytical indicators. Third, the scenario parameters are stress-test assumptions and could differ among sectors. Further studies are recommended, namely: broadening the sample, longitudinal data and application of econometric or simulation-based validation.

6. Conclusion

The research carried out here is in line with the current developments in which information technologies are becoming the basis of the infrastructural support for resilient and adaptive supply chains in the digital economy. Consequently, the research highlights the need to rethink the modern supply chain as only operationally oriented structures, organisations and processes aimed at achieving transportation efficiency and minimizing inventory levels. Rather, they have become more and more service ecosystems that are closely interconnected in a digital environment where resilience relies on the coordinated exchange of information, predictive coordination, integrated logistics informatics and

adaptive operational governance. Empirical results indicated that there is a significant positive correlation between digital integration and the resilience performance of the organizations in case of economic shocks, technological failures and combined disruption conditions, respectively. ERP systems, IoT monitoring systems, cloud coordination platforms, blockchain traceability and AI predictive analytics all help to improve visibility throughout operations, service continuity and adaptive recovery. The research has indicated that, rather than technology, implementing a digital ecosystem with synchronised operations and predictive coordination and collaborative governance mechanisms provides the greatest impact on resilience. The results also showed that predictive analytics and intelligent logistics coordination significantly shorten the propagation of disruptions and speed up the restoration of the state of operations. Organizations that implemented AI-powered forecasting systems and analytical set-ups were more resilient and resilient to uncertainty because they managed their operations proactively rather than reacting to disruption. Therefore, the ability to forecast disruptions, dynamically manage logistics operations and to have synchronized communication between the SCNs is becoming more important for organizations. A further important finding is that service-system interoperability is a factor in the formation of adaptive resilience. The findings suggest that, besides technology maturity, quality of operational synchronisation and collaborative interaction among actors in the supply chain also plays a role in the development of resilience. Organisations with sub-optimal technology achieved less continuity of operations even with technology investment, even though they had less than perfect digital infrastructure, and less interoperability. Therefore, interoperable logistics informatics architectures (IIA) that facilitate the integration of communication, the synchronisation of information flows and the co-ordination of decision making should be taken into account when planning for resilience for the future.

The study also verified the increasing strategic relevance of blockchain technologies & visibility systems based on IoT in resilient logistics operations. The technologies can be highly beneficial in providing transparency, traceability and operational trust in global supply chains. However, a number of gaps concerning cyber risks, technology interoperability, organizational adaptation, digital governance were also identified. Thus, advanced technologies are not enough: resilient ecosystems of supply chains also require coordination of governance structures that are capable of functioning resiliently in the complex digital infrastructure in uncertain situations. From a theoretical perspective, the study serves as a theoretical contribution to the development of theory in the field of supply chain resilience, where logistics informatics, predictive coordination and service-system governance are used as a whole analytical framework. The research takes an integrated way of thinking on operational sustainability by illustrating how operational sustainability is becoming more and more a part of the interconnected digital ecosystems, rather than a set of operational capabilities. The findings from the study have important implications from the practical standpoint for logistics managers, policy makers, and organizations that are adopting a digital transformation approach. In today's shifting dynamic market conditions, predictive analytics, interoperable digital platforms, cloud coordination systems and adaptive governance mechanisms can have a significant impact on operational continuity and future competitiveness. To conclude, it is clear that intelligent logistics governance and integrated digital coordination and adaptive service-system synchronization will become increasingly important to establish sustainable and stable operations and enhance resilience in global supply chains.

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