



Analyzing Resilience Capabilities of Digital Healthcare Supply Chain in the Pharmaceutical Industry: Extended Fuzzy SWARA Approach

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ARTICLE INFO	ABSTRACT
Article history: Received 25 August 2026 Received in revised form 1 October 2026 Accepted 9 October 2026 Available online 17 October 2026 Keywords: Digital Healthcare Supply Chain; Resilience Capabilities; Digital Maturity Assessment; Fuzzy SWARA; F-MARCOS	Digitalization of the supply chain enables decision-makers to effectively manage disruptive events, thereby enhancing supply chain resilience. This study identifies a comprehensive set of dimensions for active and proactive resilience capabilities based on a literature review and expert opinions gathered through the fuzzy Delphi method. Subsequently, it identifies digitally supported organizational capabilities of resilient healthcare supply chains in the pharmaceutical industry, which are then evaluated and prioritized using the improved fuzzy stepwise weight assessment ratio analysis (IMF-SWARA) method. Following this, the study analyzes various levels of digitalization and their impact on resilience by applying the fuzzy measurement alternatives and ranking according to the compromise solution (F-MARCOS) method. This approach allows for a highly accurate ranking of the impact of digitalization on resilience capabilities and accounts for decision-makers' potentially uncertain opinions within the scope of the criteria. The results indicate that Anticipation and Preparedness is the most critical resilience capability, while Strategic Leadership and Governance is the most impactful digital maturity indicator.

1. Introduction

The 21st century has witnessed various transformative events, including the technological revolution, Industry 4.0, and the COVID-19 pandemic [35-45]. Industry 4.0, commonly represented by the abbreviation I4.0 or the Fourth Industrial Revolution, encompasses various digital information technology and communications that aim to facilitate higher levels of automation or connectivity between different processes, goods, services, or people [64]. Advancements in the Internet and information technology (IT) have revolutionized the manufacturing sector through the widespread integration of digital technologies (DTs) [41-22-23]. The application and utilization of DTs have brought about transformations in organizational structure and working practices, thus necessitating different business models to address these challenges [64]. Significant changes in global business operations are impacting companies' ability to adapt, presenting challenges in the digital age [38]. The concept of digital transformation involves essential changes that focus on integrating advanced DTs into all aspects of business processes to drive innovation and operational efficiency [38-74].

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Digital technologies (DTs) are significantly influencing operations and supply chain management, helping organizations forecast future trends and identify potential disruptive events [66]. Supply chain digitalization is the process of utilizing digital technologies to modernize conventional supply chains, enabling more data-driven decision-making [72]. Digitalization enhances the capability of information processing, enabling firms to anticipate, make informed decisions, and adjust their proactivity to minimize adverse effects [76]. Digital transformation enhances the flexibility of information exchange and collaborative business processes by virtualizing supply chain (SC) processes. Resources can be utilized more effectively through digital solutions, making supply-demand decisions more efficient and effective [41]. Supply chain digitalization will increase the transparency and flexibility of firms [72]. Digitalization is crucial in increasing resilience [13]. Additionally, the supply chain network can enable traceability of each production process [78], which in turn enhances supply chain resilience [77].

Supply chain operations inherently face risks of disruption, which can lead to unfavorable operational and financial consequences [63]. The impacts of disruptions caused by events like COVID-19 must be mitigated, prompting companies to reconsider their production methods, supply chain actions, and processes. An effective strategy to prevent disruptions and minimize supply chain vulnerability is to enhance supply chain resilience (SCR), a concept recognized by both business practitioners and academia [77]. SCR is defined as the ability to anticipate, adapt to, and recover from disruptions while maintaining operational continuity. Given the interconnected nature of global supply chains, resilience plays a crucial role in ensuring the uninterrupted flow of goods and services [3]. Supply chain resilience (SCR) is considered a high-level ability that empowers companies to perceive, secure, and transform in response to changing contexts from a dynamic capability perspective. These dynamic capabilities require vital digital technologies (DTs). For instance, Additive Manufacturing enables rapid prototyping and detection, while Big Data Analytics helps companies quickly identify threats and opportunities [8]. Resilience and recovery capabilities could be reinforced through the digitalization of supply chains, alongside supply chain transparency and proficiency [72]. Fast decision-making could expedite resilience through DTs such as Industry 4.0, Big Data Analytics, Artificial Intelligence, blockchain, smart sensors, the Internet of Things, and Additive Manufacturing [8]. SCR's insertion in operational chains could help maintain effective operations in increasingly complex systems [3]. The pandemic and other significant threats, such as natural disasters, strikes, wars, and cyber-attacks, can impact supply chain performance, creating the need for healthcare SCR. This is vital for their survival, as it is an emergent property of complex socio-technical systems, influencing both acceptable and unacceptable performance under expected and unexpected conditions [13].

The COVID-19 outbreak has had a significant impact on the healthcare supply chain, specifically in relation to products, services, infrastructure, and labor directly involved in addressing the pandemic and supporting other health treatments [19-15-53]. Healthcare supply chain stakeholders have increasingly embraced new information and communication technologies (ICTs) from Industry 4.0, such as big data, cloud computing, and the Internet of Things, to enhance health treatments and administrative processes. These technologies promote the digitization and interconnectivity of processes, products, services, and people [63]. The digitalization of the supply chain can be described as leveraging traditional information systems' capabilities and implementing new advanced technologies like the Internet of Things (IoT), big data, augmented reality, unmanned aerial vehicles, and blockchain. This aims to make supply chain activities more flexible and efficient. Ideally, efficiency and flexibility should be improved across all sectors, including healthcare, which must also adapt to long-term demographic trends and sporadic events while managing costs [7].

The literature demonstrates that digital technology (DT) enhances the functionality of the Healthcare Supply Chain (HSC), but few studies have explored its effects on resilience capabilities [13]. The primary aim of this study is to present an integrated framework for assessing and ranking resilience capabilities in digital healthcare supply chains. In recent years, various powerful multi-criteria decision-making methods have been presented in the literature [17-21-24-25-26-27-28-29-55]. The specific research objectives are as follows: to explore and evaluate organizational capabilities that enhance digital resilience during crises, to apply the Improved Fuzzy SWARA method to prioritize these capabilities, to investigate the impact of varying levels of digitalization on resilience using Fuzzy MARCOS, and to offer insights to healthcare managers on enhancing supply chain resilience through digital transformation initiatives.

Finally, the main research questions in this study are as follows:

- 1 .What are the active and proactive resilience capabilities in digital healthcare supply chains?
- 2 .How are resilience capabilities prioritized?
- 3 .What is the effect of varying levels of digitalization on resilience capabilities?
4. Which digitalization indicators have the greatest impact on resilience?

The pharmaceutical industry can be considered an important case study for investigating supply chain resilience because of its distinctive features, which include strict regulations, cold chain transportation, and highly variable demand during pandemics [7-13]. However, unlike other areas of the healthcare system, the pharmaceutical supply chain is confronted by certain difficulties, which include protection from counterfeits and traceability [63]. Thus, the current research will use the pharmaceutical sector as the context of the case study.

1.1 Literature Review

This part reviews theoretical foundations and research background in key areas of the present study. First, it explains the digital transformation concept and its related technologies. Then, it discusses supply chain resilience and its dimensions. Finally, it examines the relationship between digital transformation and supply chain resilience and the existing gap in the healthcare area.

1.1.1 Digitalization and supply chain digitalization

Digitalization is defined as an action that activates significant changes through combinations of information, computing, communication, and connectivity technologies, advancing an entity and its properties [38]. Digital transformation basically renews organizational operations and capabilities in the full implementation of these technologies [42]. This transformation in digital technology has not only reshaped the modern way of living and business management models but has also arisen as a strategic preference for companies, with supply chain digitalization becoming an unavoidable trend [72]. This trend was significantly accelerated by the COVID-19 pandemic, which led to city obstruction and logistics disruptions, causing the need for remote work, paperless operations, and supply chain restructuring, which increased the speed of digital supply chain development and enabled companies to cope with the risk of disruption rapidly [77].

Digital transformation encompasses technologies such as big data analytics, the Internet of Things, and blockchain, which enable businesses to tap into the intelligence and collaboration of business processes and innovate management models [75]. Operationally, the digital transformation of supply chains is achieved through the strategic deployment of key technologies-big data analytics, cloud platforms, IoT sensors, AI, and blockchain-along the value chain. Theoretically, those technologies are not just tools but, according to the Resource-Based View, they are valuable, rare, and hard-to-imitate organizational resources [33].

1.1.2 Supply chain resilience

Supply chain resilience is the ability of the supply chain to reduce risks of interruptions, both internal operational failures and external natural disasters, control the effects of these interruptions, and recover rapidly with adaptive strategies, as well as rebuild or improve the robustness of the supply chain with rapid response strategies and structural control [75]. The most comprehensive definition of supply chain resilience has been provided by [50], who state that supply chain resilience refers to the ability of the supply chain to adapt to sudden unforeseen events and disruptions, maintain the stability of the supply chain structure and functions, and recover from disruptions and unforeseen events. Supply chain resilience has four different dimensions: readiness, response, recovery, and growth [58-70]. Most research considers SCR as a two-dimensional capability structure: proactive capability (readiness before risk) and reactive capability (activities after risk has occurred) [77]. Various researchers have identified different resilience capabilities. Furstenu et al. [13] identified long-term collaborative planning and strategic alliances in healthcare. Zhao et al. [77] identified absorptive, response, and recovery capabilities. Shi et al. [56] studied adaptation, response, and recovery. Michel-Villarreal et al. [44] focused on flexibility, redundancy, collaboration, visibility, and agility. [35] emphasized end-to-end visibility. Tortorella et al. [63-64-65] explored monitoring, anticipating, responding, and learning. Zouari et al. [80] proposed 14 capabilities, including flexibility, visibility, adaptability, anticipation, recovery, collaboration, and financial strength. Li et al. [39] defined five capabilities: anticipate, prepare, prevent, respond, and adapt. Ali et al. [2] proposed readiness, response, and recovery. Balci et al. [6] included prepare, respond, recover, adapt, and growth. Wang et al. [70] included redundant resources, financial strength, collaboration, and visibility. Although supply chain resilience has attracted extensive attention, there is an urgent need to further explore how digital empowerment can strengthen supply chain resilience from various dimensions and drive its development. Based on the existing research, this paper classifies the relationship between digital empowerment and supply chain resilience into the following dimensions (see Table 1).

Table 1
Conceptual Classification of Supply Chain Resilience Capabilities with Corresponding References

Studies																
Conceptual Dimensions	Resilience Capabilities	Zouari <i>et al.</i> , [80]	Michel-Villarreal <i>et al.</i> , [44]	Tortorella <i>et al.</i> , [64]	Ivanov, [35]	Tortorella <i>et al.</i> , [63]	Furstenau <i>et al.</i> , [13]	Zhao <i>et al.</i> , [77]	Shi <i>et al.</i> , [56]	Tortorella <i>et al.</i> , [65]	Li <i>et al.</i> , [39]	Liu, [41]	Wang <i>et al.</i> , [70]	Ali <i>et al.</i> , [2]	Balci <i>et al.</i> , [6]	Current Studies
Anticipation & Preparedness	Anticipate	✓		✓		✓	✓				✓					✓
	Monitor			✓		✓	✓									✓
	Prepare										✓				✓	✓
	Prevent										✓					
	Readiness													✓		
	Plan														✓	
	Response			✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓

Studies																
Conceptual Dimensions	Resilience Capabilities	Zouari <i>et al.</i> , [80]	Michel-Villarreal <i>et al.</i> , [44]	Tortorella <i>et al.</i> , [64]	Ivanov, [35]	Tortorella <i>et al.</i> , [63]	Furstenau <i>et al.</i> , [13]	Zhao <i>et al.</i> , [77]	Shi <i>et al.</i> , [56]	Tortorella <i>et al.</i> , [65]	Li <i>et al.</i> , [39]	Liu, [41]	Wang <i>et al.</i> , [70]	Ali <i>et al.</i> , [2]	Balci <i>et al.</i> , [6]	Current Studies
Absorption & Response	Absorptive							✓								
	Agility		✓									✓				✓
	Redundancy		✓										✓			✓
	Cope with changes									✓					✓	✓
Recovery & Adaptation	Recovery	✓						✓	✓	✓				✓	✓	✓
	Learn			✓		✓	✓			✓						✓
	Adaption	✓							✓	✓	✓					✓
	Flexibility	✓	✓									✓	✓			✓
	Growth														✓	
Collaboration & Visibility	Collaboration	✓	✓										✓			✓
	Visibility	✓	✓									✓	✓			✓
	End-to-end visibility				✓											
	Situational awareness									✓						
	Knowledge access									✓						
Resources & Capacity Building	Operational capacity												✓			
	Financial strength	✓								✓			✓			✓
	Capacity	✓														
	Efficiency	✓														
Strategic & Structural Capabilities	Dispersion	✓														
	Security	✓														
	Market Position	✓														
	Organization	✓														

Table 1 presents an overview of the resilient capabilities that have been recognized within important literature. As can be seen in Table 1, capabilities like response, recovery, adaptation, collaboration, flexibility, and visibility have been the subject of the greatest amount of scholarly focus. On the other hand, capabilities like growth, readiness, and some proactive capabilities like prevention and planning have been addressed to a lesser extent by scholars.

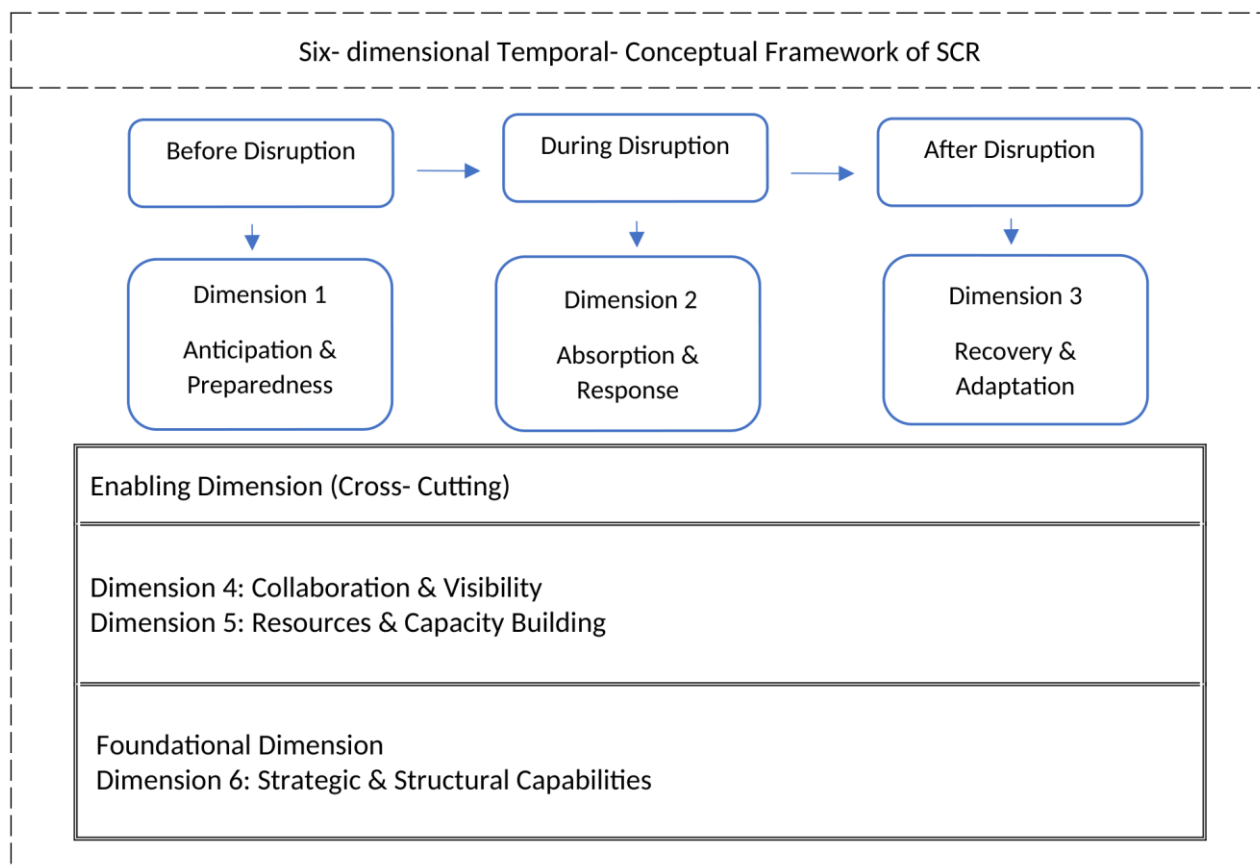


Fig. 1. Six-Dimensional SCR Framework

Figure 1 describes the timeline for resilience capabilities. Based on the timeline, the capabilities will be categorized into three major categories, which include proactive capabilities before the disruption occurs (Dimension 1), reactive capabilities that occur during disruption (Dimension 2), and recovery capabilities after disruption (Dimension 3). The two enabling dimensions are collaboration and visibility (Dimension 4) and resource and capacity building (Dimension 5). Besides, there is the sixth dimension called Strategic and Structural Capabilities.

1.1.3 The effect of digitalization on supply chain resilience

The COVID-19 pandemic has highlighted the importance of research into supply chain resilience and, more specifically, the use of digital technology to mitigate disruption [47]. Furstenau *et al.* [13] emphasize the importance of digitalization in improving resilience. Building this resilience typically involves developing special capabilities and processes in advance. Of course, these capabilities are increasingly dependent on digital tools and data [38]. Digital technologies, such as the Internet of Things and artificial intelligence, can also optimize the inventory management system and make the forecasting of demand more precise, which will allow enterprises to respond better to external pressures and thus make the supply chain more robust [75]. An organization's degree of digital transformation - its ability to harness digital technology in the service of supply chain management - has a profound impact on how well the supply chain can anticipate disruptions and adapt accordingly [38].

1.1.4 Healthcare supply chain

The healthcare supply chain of technology integration is expected to enhance the ability to provide effective healthcare services with the aid of innovative technologies that provide maximum satisfaction to the patients. It is expected that the supply chain of technology integration enables the healthcare supply chain to collaborate in a better manner and develop supply chain resilience [3].

1.1.4.1 Resilient healthcare supply chain

Resilient healthcare is the ability of the health system to adapt its operations before, during, or after changes and disruptions in order to ensure the desired performance under expected and unexpected circumstances [32]. The challenges posed by the COVID-19 pandemic have highlighted the existence of substantial weaknesses within the HSC, particularly in relation to health services directly associated with the mitigation of the pandemic and related to other preventive treatments [15-19-53].

1.1.4.2 Digital healthcare supply chain

The healthcare industry has been the pioneer in the use of digital platform technologies, which are creating digital operations solutions to support the development of digital healthcare service processes [77]. The idea of “healthcare supply chain 4.0” reflects the application of Industry 4.0 technologies in the HSC [13]. In emergencies like the COVID-19 pandemic, studies regarding healthcare in terms of digital transformation have shown different perspectives. For example, Ohannessian *et al.* [48] and [73] believed that integrated intelligent healthcare systems based on novel health digital applications, such as artificial intelligence, big data, 5G, Internet-of-Things, cloud computing technology, sensor technology, telehealth service, and mobile health applications, play an important role in blocking the spread of the pandemic. This part reviews theoretical foundations and research background in key areas of the present study. First, it explains the digital transformation concept and its related technologies. Then, it discusses supply chain resilience and its dimensions. Finally, it examines the relationship between digital transformation and supply chain resilience and the existing gap study in the healthcare area.

1.1.5 Digital healthcare supply chain assessment framework

According to Stank *et al.*, [59], more research has to be carried out regarding the impact of digitalization on SC. More specifically, about the healthcare industry, this last observation confirms the statement made by [49], which states that investment has to be measured in terms of efforts required and capabilities available with regard to future initiatives. [14] consider that a precondition with regard to the realization of the maximal potential of digitalization technologies is the formulation of a strategic vision [7].

Another study indicates that the reason why recent studies have been focusing on individual digital tools is that companies are able to implement a number of tools at once, and thus the degree of adoption of various digital tools may affect SC resilience [44]. Most of the models in the digitalization context are about digital transformation implementation methodologies, or the models are developed for organizations, not the supply chain. So, there are gaps in assessing the digital maturity of a supply chain, especially in healthcare. This model is developed for assessing the digital maturity of a healthcare supply chain based on a comparative analysis. For the first step, abstracts of about 184 papers were reviewed. 40 papers were chosen. Most of the chosen papers were review

models that reviewed previous models in the context of the digital maturity framework, digital supply chain framework, and digital healthcare framework. In the next step, 12 papers were chosen. Then, a comparative analysis was conducted for the purpose of developing a digital healthcare supply chain assessment framework. The most frequent indicators were determined, then categorized, and ordered.

Table 2
Digital Maturity Dimensions and Indicators for Healthcare Supply Chain

Studies														
Main Digital Dimensions	Digital Maturity Indicators	Hein-Pensel <i>et al.</i> , [30]	Govindan & Arampatzis, [18]	Agostino & Costantini, [1]	Haryanti <i>et al.</i> , [20]	Gökalp & Martinez, [16]	Büyükoğkan & Göçer, [9]	Hellweg <i>et al.</i> , [31]	Kim & Namkoong, [37]	Liaw & Godinho, [40]	Ibrahim <i>et al.</i> , [34]	Fava & Lapão, [12]	Woods <i>et al.</i> , [71]	Current study
Strategic Leadership & Governance	Strategy Development to Industry 4.0	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓
	Leadership Support	✓	✓							✓			✓	
	Financial Support & Investment	✓	✓	✓	✓	✓		✓		✓				✓
	Portfolio Management	✓			✓	✓		✓		✓				
	Regulatory Compliance & Cybersecurity Governance	✓	✓			✓		✓	✓	✓				✓
	Culture Development	✓			✓	✓	✓	✓	✓				✓	✓
Workforce & Technology Integration	Core Competency & Skill Development	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓
	Continuous Learning & Knowledge Growth	✓			✓	✓	✓	✓				✓	✓	✓
	Employee Technology Adoption	✓					✓	✓		✓			✓	
Integrated Digital Operations	horizontal integration	✓	✓		✓	✓	✓	✓					✓	✓
	vertical integration		✓		✓	✓	✓	✓						
	Ecosystem Digital Collaboration	✓	✓				✓	✓					✓	
Automation	Cognitive Process Automation	✓	✓				✓	✓						✓
	Physical Process Automation	✓	✓				✓	✓						
	Self-Optimizing Automation (Adaptive Hybrid Automation)					✓		✓						
Technology Deployment	Core IT Infrastructure & Systems	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
	Digitized Physical Assets		✓				✓	✓	✓		✓		✓	✓

Studies														
Main Digital Dimensions	Digital Maturity Indicators	Hein-Pensel <i>et al.</i> , [30]	Govindan & Arampatzis, [18]	Agostino & Costantini, [1]	Haryanti <i>et al.</i> , [20]	Gökalp & Martinez, [16]	Büyükoçkan & Göçer, [9]	Hellweg <i>et al.</i> , [31]	Kim & Namkoong, [37]	Liaw & Godinho, [40]	Ibrahim <i>et al.</i> , [34]	Fava & Lapão, [12]	Woods <i>et al.</i> , [71]	Current study
	Cyber-Physical Integration Capability(interoperability)	✓	✓				✓	✓					✓	
	Cybersecurity Infrastructure and management	✓			✓	✓		✓		✓			✓	✓
Data-Driven Intelligence & Insights	Core Data Infrastructure	✓	✓		✓	✓		✓	✓	✓	✓		✓	✓
	Real-Time Data Utilization		✓				✓	✓			✓	✓		
	Advanced Analytics & Insights	✓	✓			✓	✓	✓			✓		✓	✓
Customer & Experience	Customer Empowerment & Accessibility		✓		✓		✓	✓	✓		✓		✓	✓
	Digital Experience Optimization	✓			✓		✓	✓			✓		✓	✓
	Organizational understanding & Insight	✓					✓	✓	✓		✓		✓	✓
Healthcare-Specific Digital Solutions	Remote Healthcare & Patient Engagement									✓	✓	✓		✓
	Connected Devices & IoT		✓								✓			
	Digital Records & Interoperability									✓	✓			
	Advanced Technologies & Diagnostics									✓	✓			
	Digital Identification & Security									✓				

While a lot of scholarly work has been conducted regarding digital transformation and resilience in supply chain management, there still exist some gaps in this area. First of all, no prior empirical research prioritized the digitally-enabled resilience capabilities in the healthcare sector. Secondly, digital maturity models were not developed specifically for pharmaceutical supply chain. Thirdly, there is no literature applying IMF-SWARA and F-MARCOS methods together in order to analyze the influence of the level of digitalization on the resilience capabilities. Thus, the main contributions (novelties) of this research are as follows:

1. Identifying and prioritizing resilience capabilities in digital healthcare supply chains using the IMF-SWARA method.
2. Development of a digital maturity model for healthcare supply chains consisting of 30 indicators distributed over 8 dimensions.

3. The evaluation of the effect of digitalization maturity levels on resilience capabilities using the F-MARCOS approach.
4. Insights from the pharmaceutical industry regarding cold chain, traceability, and regulatory compliance problems.
5. Methodologically integrating IMF-SWARA and F-MARCOS for the first time in a healthcare supply chain context research methodology and questionnaire design.

1.2 Literature Review

As seen in Table 2, all the indicators in the eight dimensions, such as Strategy Development to Industry 4.0; Financial Support and Investment; Regulatory Compliance and Cybersecurity Governance; Culture Development; Core Competency and Skill Development; Continuous Learning and Knowledge Growth; Horizontal Integration; Cognitive Process Automation; Core IT Infrastructure and Systems; Digitized Physical Assets; Cybersecurity Infrastructure and Management; Core Data Infrastructure; Advanced Analytics and Insights; Customer Empowerment and Accessibility; Digital Experience Optimization; Organizational Understanding and Insight; and Remote Healthcare and Patient Engagement are represented. Likewise, as seen in Table 1, all fourteen indicators for four conceptual dimensions of the Resilience Capabilities Framework: Anticipate, Monitor, Prepare (Anticipation and Preparedness); Response, Agility, Redundancy, Cope with changes (Absorption and Response); Recovery, Learn, Adaptation, Flexibility (Recovery and Adaptation); and Collaboration, Visibility, Financial strength (Collaboration and Visibility) are represented, implying that currently, there is no study that has empirically assessed and prioritized those particular indicators of digitalization and resilience in the pharmaceutical supply chain sector. This implies that no research has been conducted that explored how digitalization maturity levels influence particular resilience dimensions. Thus, the primary research problem is the lack of empirical evidence.

While research on supply chain digitalization and resilience is expanding, a crucial area still needs attention: how digitalization can enhance specific resilience capabilities in healthcare supply chains, especially within the pharmaceutical sector. Most existing studies have either explored the broad link between digital technologies and overall supply chain resilience or focused solely on particular digital tools and the process of organizational transformation. However, there has been insufficient empirical research aimed at systematically identifying and ranking digitally enabled resilience capabilities within healthcare supply chains. Additionally, maturity models for digitalization have not been adequately developed or evaluated specifically for pharmaceutical supply chains. This industry poses unique challenges such as stringent regulatory demands, requirements for cold-chain logistics, traceability issues, and unpredictable demand during crises. Furthermore, an integrated empirical examination of how varying levels of digital maturity impact distinct resilience capabilities in this field is absent from current literature. Addressing this gap holds considerable importance for both academic inquiry and practical applications. From a research perspective, the examination of resilience capabilities and digital maturity from an integrated perspective can help in understanding the relationship between supply chain digitalization and resilience within the healthcare industry. From a management perspective of the pharmaceutical supply chain, it helps in knowing the resilience capabilities which need more focus and how digital maturity impacts them. This becomes necessary because pharmaceutical supply chains heavily depend on continuity of supply and thus are associated with regulatory compliance, product traceability, cold chain requirements, and response to disruptions. Hence, a systematic evaluation of digitally enabled resilience capabilities can assist in bridging the gap between digital transformation programs and resilience supply chain management. As a result, this study aims to construct an integrated framework for the assessment and

prioritization of resilience capabilities in digital health supply chains within the pharmaceutical sector. In particular, the objective of the research is to: (1) discover and measure the active and proactive resilience capabilities that can be enhanced with the help of digitalization; (2) rank the resilience capabilities using the improved fuzzy stepwise weight assessment ratio analysis (IMF-SWARA) technique; (3) investigate how different levels of digital maturity impact resilience capabilities using fuzzy measurement of alternatives and ranking according to the compromise solution (F-MARCOS); and (4) present the digital maturity factors that have the greatest influence on resilience capabilities. The objectives are explained through the following questions of the study: (1) Which active and proactive resilience capabilities do digital healthcare supply chains possess? (2) How can those resilience capabilities be prioritized? (3) What is the impact of varying levels of digitalization on resilience capabilities? (4) What digitalization factors are the most vital for resilience?

2. Methodology

This study began by defining the core decision-making problem. The selected criteria are the healthcare supply chain resiliency factors such as flexibility, redundancy, agility, visibility, and collaboration. As alternatives, it considered supply chain digital maturity level indicators such as strategic leadership, workforce and technology integration, integrated digital operations, and automation. Figure 1 outlines the research methodology. First, it identified resiliency factors from the existing literature and ranked them in descending order of importance. Then it collected linguistic evaluations from experts using a structured questionnaire and processed these evaluations through the IMF-SWARA method. In this step, pairwise comparisons were converted into triangular fuzzy numbers, allowing it to compute the values of k_j , q_j and w_j . After defuzzification, it obtained the final importance weight for each resiliency criterion. Next, it determined the digital maturity indicators by combining a literature review with expert input. To evaluate these indicators, it constructed a fuzzy decision matrix based on a nine-point linguistic scale, which captured how strongly each indicator influenced each resiliency factor according to expert judgments. Finally, it applied the F-MARCOS method to derive utility functions relative to fuzzy ideal and anti-ideal solutions, resulting in a prioritized ranking of the digital maturity indicators.

2.1 Improved Fuzzy stepwise Weight Assessment Ratio Analysis Method (IMF-SWARA)

The SWARA method, developed by Keršulienė *et al.*, [36], is used to determine the weights of criteria in a multi-criteria decision-making process [11]. The relative importance of each option is then determined for each criterion, and the ranking of the options is done correspondingly [46]. This method is different from the other methods in the sense that the experts can easily participate and make decisions regarding the criteria and prioritization [54-79]. The main benefits of the SWARA method are as follows: (1) the method has a simple and transparent mathematical framework, which enables the effective use of the method in group decision situations in which the experts can share their views; (2) the mathematical complexity of the method does not increase when the number of criteria increases, making the method suitable for use in decision models with many decision attributes; and (3) the method enables the processing of the data using various scales of evaluation, making the method adaptable for use in various situations [11].

The Fuzzy SWARA technique enables experts to effectively manage difficult and uncertain decision-making problems with simple language, making them more real and reliable [43]. Based on this approach, Vrtačić *et al.* [69] proposed improvements to this technique and referred to it as

Improved Fuzzy SWARA (IMF-SWARA). This technique is a reliable and organized way to manage complex decisions and presents flexible and practical solutions to real-world problems [4].

The Fuzzy SWARA (F-SWARA) method has emerged as a favorite tool for calculating weights, with researchers using it for a variety of fields, including risk management [46], lean supply chains [54], etc. Then came the IMF-SWARA, developed by Vrtagić *et al.* [69], which resolved the evaluation scale problem and produced more realistic results. Furthermore, the evaluation scale has been extended to a nine-point scale to cover all opinions. The steps involved in calculating the relative weights of the criteria using the fuzzy comparison scale are as follows: [79].

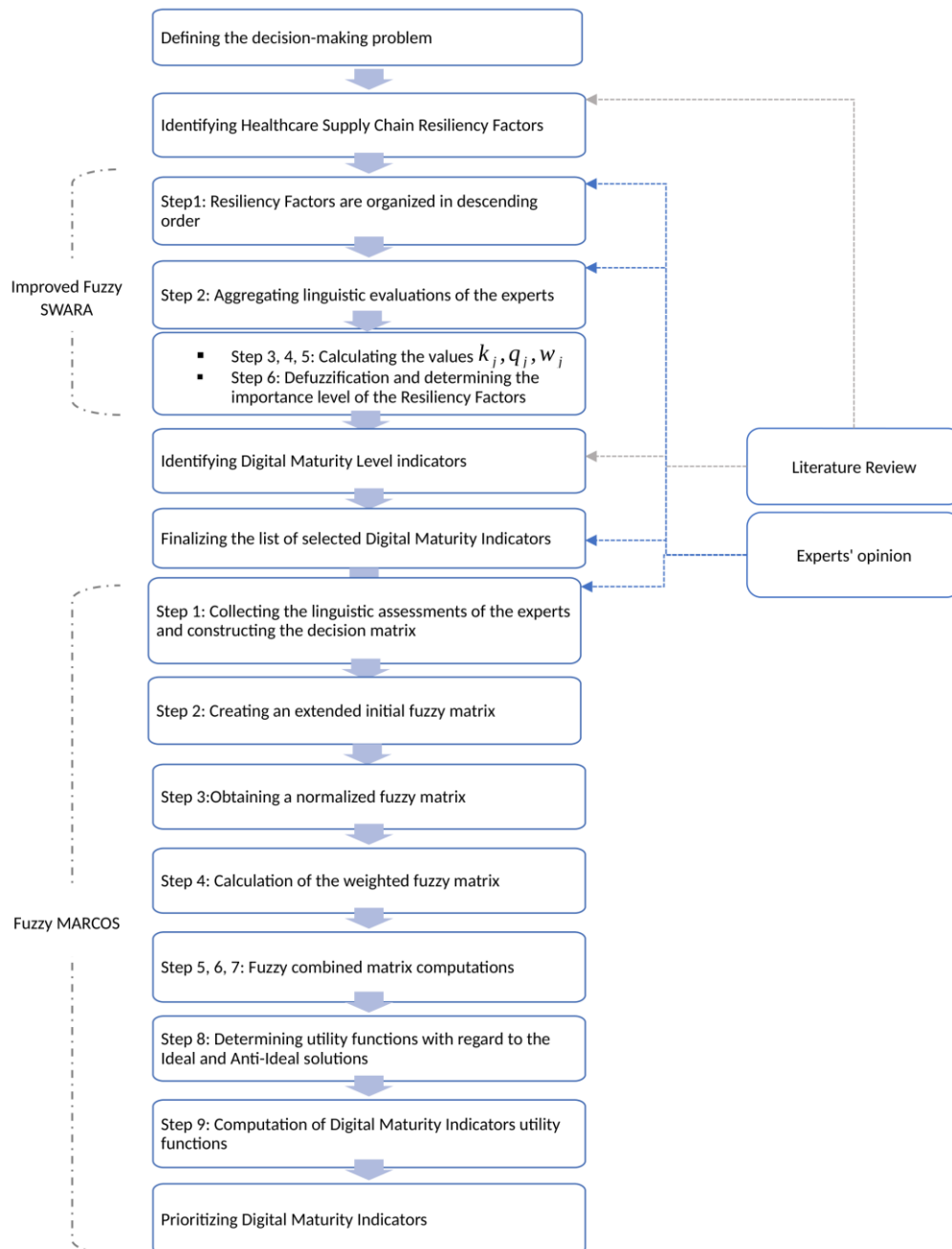


Fig.2. Overview of applied research methodology

Step 1: After all criteria are determined, they are arranged in descending order according to their importance. The most important criterion is placed first, and the least important is placed last. The fuzzy linguistic scale used for evaluation is presented in Table 3 based on [52-57].

Step 2: Beginning with the second criterion, the expert assigns a relative importance score $\bar{s}_j$ to criterion j compared to the immediately higher-ranked criterion (j-1). The linguistic evaluations are collected using the nine-point fuzzy scale shown in Table 3.

Data collection for IMF-SWARA: To determine the weights for the resiliency factors, we used the expert opinions collected using the IMF-SWARA approach. A structured questionnaire was administered to a group of 7 experienced professionals in the healthcare supply chain field. The questionnaire gathered information on the first two steps of the IMF-SWARA approach. First, the respondents were asked to rate all factors from most important to least important. Then, for each factor, the respondents were asked to rate how much more or less significant the factor is compared to the factor ranked above it in the importance ranking. The respondents used a set of predetermined linguistic terms (such as "Weak importance" and "Extreme importance") as shown in Table 3.

Step 3: Calculation of the fuzzy coefficient $\bar{k}_j(1)$:

$$\bar{k}_j = \begin{cases} \bar{1} & j = 1 \\ \bar{s}_j & j > 1 \end{cases} \quad (1)$$

Step 4: Calculation of the calculated weights $\bar{q}_j(2)$:

$$\bar{q}_j = \begin{cases} \bar{1} & j = 1 \\ \frac{\bar{q}_{j-1}}{\bar{k}_j} & j > 1 \end{cases} \quad (2)$$

Step 5: Calculate the fuzzy weight coefficients using Equation (3):

$$\bar{w}_j = \frac{\bar{q}_j}{\sum_{j=1}^m \bar{q}_j} \quad (3)$$

Table 3
Fuzzy comparison scale

Linguistic Scale	Code	Saaty and Vargas scale	Triangular fuzzy numbers	Fuzzy decimal expression
Equal importance	EI	1	(0, 0, 0)	(0.000, 0.000, 0.000)
Weak importance	WI	2	(2/9, 2/8, 2/7)	(0.222, 0.250, 0.286)
Moderate importance	MI	3	(2/8, 2/5, 2/6)	(0.250, 0.286, 0.333)
Moderate plus importance	MP	4	(2/7, 2/6, 2/5)	(0.286, 0.333, 0.400)
Essential importance	LI	5	(2/6, 2/5, 2/4)	(0.333, 0.400, 0.500)
Demonstrated importance	DI	6	(2/5, 2/4, 2/3)	(0.400, 0.500, 0.667)
Strong importance	SI	7	(2/4, 2/3, 1)	(0.500, 0.667, 1.000)
Absolute importance	AI	8	(2/3, 1, 3/2)	(0.667, 1.000, 1.000)
Extreme importance	EXI	9	(1, 1, 1)	(1.000, 1.000, 1.000)

IMF-SWARA [69-79]: In this equation, $\overline{w_j}$ represents the fuzzy relative weight of criterion j , and m is the total number of criteria.

Step 6: The defuzzification of $\overline{w_j}$ happens when the weights of the criteria are required to be ranked with crisp numbers as per Eq. (4):

$$x_{ij} = \frac{(x_{ij}^u - x_{ij}^l) + (x_{ij}^m - x_{ij}^l)}{3} + x_{ij}^l \quad (4)$$

where x_{ij} represents the evaluation of the i th alternative with respect to the j th decision criterion. The triangular fuzzy number is represented as (l, m, u) , where l , m , and u represent the smallest, most representative, and largest possible values, respectively [69].

2.2 Fuzzy Measurement Alternatives and Ranking According to Compromise Solution Method (F-MARCOS)

One of the MCDM methods currently being used is the MARCOS method, which is proposed by Stević et al. (2020). The basic principle behind the MARCOS technique is finding the solution based on the relation among alternatives and reference values [5], which helps decision-makers make proper decisions [79].

MARCOS (Measurement Alternatives and Ranking according to the Compromise Solution) is a relatively new MCDM technique. This technique identifies the preferability of alternatives based on the relation among alternatives and reference values. The process of defining the preferences for the decision-making process is done by using utility functions. These functions demonstrate the location of the alternatives with respect to the ideal and anti-ideal solutions [60]. The best alternative is the one closest to the ideal solution and farthest from the anti-ideal solution [61-67]. Similar to the TOPSIS technique, the best alternative is the one closest to the ideal solution and farthest from the anti-ideal solution [51]. The MARCOS technique was successfully used for sustainable supplier selection [61], human resource evaluation [61], and software selection [57]. The technique was also used for the calculation of fuzzy numbers [60], D numbers [10], and grey numbers [5].

As a holistic system, MARCOS addresses some of the limitations of other MCDM techniques, which are time-consuming with involved calculations, often require set parameters, and sometimes fail to account for how distance is important comparatively [79].

F-MARCOS was developed to ensure that more practical solutions are obtained with more robust, usable, and practical outputs by capturing decision-makers' opinions under ambiguous conditions [60]. Fuzzy theory is linked to linguistic or verbal ambiguities that allow it to interact with vagueness [79]. The approach also establishes the connections between the relationships of the alternatives and the fuzzy sets of the alternative values and provides the degrees of the utilities of the alternatives relative to the fuzzy ideal solution and the fuzzy anti-ideal solution [67].

A number of research articles have been published using MARCOS in fuzzy environments, such as e-survey quality assessment, railway crossing safety evaluation, multiple digital transformation strategies selection, hydrogen buses selection, choice criteria for sustainable suppliers selection, assessment of outage losses during regional power distribution networks, selection of organizational structure for hospitals, selection of reach stackers for container terminals, and selection of green mining strategy. A fuzzy linguistic scale for preference during decision-making for F-MARCOS is presented in Table 4. The steps involved in the F-MARCOS method are presented as follows [79-5-68]:

Step 1: Firstly, the fuzzy decision matrix is defined as ($\tilde{I\tilde{X}}$), and the initial decision matrix is formed with n criteria and m alternatives. (5)

$$\tilde{I\tilde{X}} = \begin{matrix} \tilde{A}_1 \\ \tilde{A}_2 \\ \dots \\ \tilde{A}_m \end{matrix} \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \quad (5)$$

Data Collection for F-MARCOS: To construct the fuzzy decision matrix for F-MARCOS, a matrix-form questionnaire was administered to the experts. The rows represented the digital healthcare supply chain maturity indicators (alternatives), and the columns represented the resiliency factors (criteria). The experts assessed the strength of influence of each indicator on each factor using the linguistic terms described in Table 4. The results were transformed into triangular fuzzy numbers to construct the aggregated initial decision matrix $\tilde{X}$, as described in Equation (5) [60].

Table 4

Linguistic scale for solutions [79]

Linguistic Scale	Code	Fuzzy numbers
Extremely Poor	EP	(1,1,1)
Very Poor	VP	(1,1,3)
Poor	P	(1,3,5)
Medium poor	MP	(3,3,5)
Medium	M	(3,5,5)
Medium good	MG	(5,5,7)
Good	G	(5,7,7)
Very good	VG	(7,7,9)
Extremely good	EG	(7,9,9)

Step 2: Formation of an extended initial fuzzy matrix ($\tilde{X}$). To perform the extension operation, the fuzzy anti-ideal solution $\tilde{A}(AI)$ and the fuzzy ideal solution $\tilde{A}(ID)$ are determined. (6)

$$\tilde{X} = \begin{matrix} \tilde{A}(AI) \\ \tilde{A}_1 \\ \tilde{A}_2 \\ \dots \\ \tilde{A}_m \\ \tilde{A}(ID) \end{matrix} \begin{bmatrix} \tilde{x}_{ai1} & \tilde{x}_{ai2} & \dots & \tilde{x}_{ain} \\ \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \\ \tilde{x}_{id1} & \tilde{x}_{id2} & \dots & \tilde{x}_{idn} \end{bmatrix} \quad (6)$$

The fuzzy solution $\tilde{A}(AI)$ is the worst solution, while the fuzzy solution $\tilde{A}(ID)$ is the best solution. Based on the type of the criteria, the fuzzy solutions $\tilde{A}(AI)$ and $\tilde{A}(ID)$ are determined using Equations (7) and (8). B belongs to the maximizing criteria group, while C belongs to the minimization criteria group.

$$\tilde{A}(Al) = \min_i \tilde{x}_{ij} \text{ if } j \in B \text{ and } \max_i \tilde{x}_{ij} \text{ if } j \in C \quad (7)$$

$$\tilde{A}(ID) = \max_i \tilde{x}_{ij} \text{ if } j \in B \text{ and } \min_i \tilde{x}_{ij} \text{ if } j \in C \quad (8)$$

Step 3: Derivation of the normalized fuzzy matrix $\tilde{N} = [\tilde{n}_{ij}]_{m \times n}$ by applying Equations (9) and (10):

$$\tilde{n}_{ij} = (n_{ij}^l, n_{ij}^m, n_{ij}^n) = \left(\frac{x_{id}^l}{x_{ij}^n}, \frac{x_{id}^m}{x_{ij}^m}, \frac{x_{id}^l}{x_{ij}^l} \right) \text{ if } j \in C \quad (9)$$

$$\tilde{n}_{ij} = (n_{ij}^l, n_{ij}^m, n_{ij}^n) = \left(\frac{x_{ij}^n}{x_{id}^n}, \frac{x_{ij}^m}{x_{id}^m}, \frac{x_{ij}^l}{x_{id}^l} \right) \text{ if } j \in B \quad (10)$$

where $x_{ij}^l, x_{ij}^m, x_{ij}^n$ and $x_{id}^l, x_{id}^m, x_{id}^n$ represent the components of the fuzzy matrix $\tilde{X}$.

Step 4: Computation of the weighted fuzzy matrix $\tilde{V} = [\tilde{v}_{ij}]_{m \times n}$. The weighted fuzzy matrix $\tilde{V}$ results from the product of the normalized fuzzy matrix $\tilde{N}$ and the fuzzy weight coefficients of the criterion $\tilde{w}_j$, as expressed in Equation (11).

$$\tilde{v}_{ij} = (v_{ij}^l, v_{ij}^m, v_{ij}^n) = \tilde{n}_{ij} \otimes \tilde{w}_j = (n_{ij}^l \times w_j^l, n_{ij}^m \times w_j^m, n_{ij}^n \times w_j^n) \quad (11)$$

Step 5: Calculate the fuzzy summation matrix $\tilde{S}_i$ by using Equation (12):

$$\tilde{S}_i = \sum_{j=1}^n \tilde{v}_{ij} \quad (12)$$

In this equation, $\tilde{S}_i(s_i^l, s_i^m, s_i^n)$ represents the sum of the fuzzy matrix $\tilde{V}$.

Step 6: Calculate the utility degree of alternatives $\tilde{K}_i$ by using Equations (13) and (14):

$$\tilde{K}_i^- = \frac{\tilde{S}_i}{\tilde{S}_{ai}} = \left(\frac{s_i^l}{s_{ai}^n}, \frac{s_i^m}{s_{ai}^m}, \frac{s_i^n}{s_{ai}^l} \right) \quad (13)$$

$$\tilde{K}_i^+ = \frac{\tilde{S}_i}{\tilde{S}_{id}} = \left(\frac{s_i^l}{s_{id}^n}, \frac{s_i^m}{s_{id}^m}, \frac{s_i^n}{s_{id}^l} \right) \quad (14)$$

Step 7: The fuzzy combined matrix $\tilde{T}_i$ is calculated by using Equation 15. At this point, a new fuzzy number $\tilde{D}$ has to be calculated by using Equation 16.

$$\tilde{T}_i = \tilde{t}_i = (t_i^l, t_i^m, t_i^n) = \tilde{K}_i^- \oplus \tilde{K}_i^+ = (k_i^{-l} + k_i^{+l}, k_i^{-m} + k_i^{+m}, k_i^{-n} + k_i^{+n}) \quad (15)$$

$$\tilde{D} = (d^l, d^m, d^n) = \max_i \tilde{t}_{ij} \quad (16)$$

Next, we carry out the defuzzification of the value $\tilde{D}$ to obtain $df_{crisp} = \frac{l+4m+n}{6}$.

Step 8: With the aid of Equations (17) and (18), the utility functions for the ideal solution $f(\tilde{K}_i^+)$ and the anti-ideal solution $f(\tilde{K}_i^-)$ can be derived.

$$f(\tilde{K}_i^+) = \frac{\tilde{K}_i^-}{df_{crisp}} = \left(\frac{k_i^{-l}}{df_{crisp}}, \frac{k_i^{-m}}{df_{crisp}}, \frac{k_i^{-n}}{df_{crisp}} \right) \quad (17)$$

$$f(\tilde{K}_i^-) = \frac{\tilde{K}_i^+}{df_{crisp}} = \left(\frac{k_i^{+l}}{df_{crisp}}, \frac{k_i^{+m}}{df_{crisp}}, \frac{k_i^{+n}}{df_{crisp}} \right) \quad (18)$$

Next, defuzzification is carried out for the value $\tilde{K}_i^-, \tilde{K}_i^+, f(\tilde{K}_i^-), f(\tilde{K}_i^+)$, followed by the next:

Step 9: Calculate the utility function for the alternatives $f(K_i)$ using Equation (19). The alternative with the highest utility value is selected [79].

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}} \quad (19)$$

3. Results

In the first step, a comprehensive set of resilience capabilities for digital healthcare supply chains was identified through an extensive literature review. Based on the conceptual classification presented in Table 1, a total of twenty-nine resilience capabilities were initially extracted and categorized across six conceptual dimensions: Anticipation and Preparedness, Absorption and Response, Recovery and Adaptation, Collaboration and Visibility, Resources and Capacity Building, and Strategic and Structural Capabilities.

Table 5

An innovative scale to assess the feasibility of solutions

Linguistic Scale	Code	Fuzzy numbers
Extremely Poor	1 EP	(1, 1, 1)
Very Poor	2 VP	(1, 1, 3)
Poor	3 P	(1, 3, 5)
Medium poor	4 MP	(3, 3, 5)
Medium	5 M	(3, 5, 5)
Medium good	6 MG	(5, 5, 7)
Good	7 G	(5, 7, 7)
Very good	8 VG	(7, 7, 9)
Extremely good	9 EG	(7, 9, 9)

An initial questionnaire was then administered to a panel of seven experienced professionals in the pharmaceutical supply chain sector, all possessing at least ten years of relevant expertise in healthcare logistics, risk management, or pharmaceutical operations. Based on their expert suggestions, no capabilities from the primary list were removed; however, the list was refined and finalized to six key resilience criteria (C1-C6) that were deemed most relevant for the subsequent prioritization process (see Table 6).

Table 6

Initial fuzzy decision matrix extended

	Linguistic Ratings						Ratings with TFNs					
	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6
A1	VG	G	EG	EG	G	EG	(7, 7, 9)	(5, 7, 7)	(7, 9, 9)	(7, 9, 9)	(5, 7, 7)	(7, 9, 9)
A2	MG	VG	VG	VG	MG	VG	(5, 5, 7)	(7, 7, 9)	(7, 7, 9)	(7, 7, 9)	(5, 5, 7)	(7, 7, 9)
A3	M	MG	MG	G	M	VG	(3, 5, 5)	(5, 5, 7)	(5, 5, 7)	(5, 7, 7)	(3, 5, 5)	(7, 7, 9)
A4	M	G	G	MG	G	G	(3, 5, 5)	(5, 7, 7)	(5, 7, 7)	(5, 5, 7)	(5, 7, 7)	(5, 7, 7)
A5	G	G	G	M	VG	MG	(5, 7, 7)	(5, 7, 7)	(5, 7, 7)	(3, 5, 5)	(7, 7, 9)	(5, 5, 7)
A6	MG	VG	MG	MG	M	G	(5, 5, 7)	(7, 7, 9)	(5, 5, 7)	(5, 5, 7)	(5, 7, 7)	(5, 7, 7)
A7	VG	M	G	VG	VG	VG	(7, 7, 9)	(3, 5, 5)	(5, 7, 7)	(7, 7, 9)	(7, 7, 9)	(7, 7, 9)
A8	G	MP	MG	MG	G	MG	(5, 7, 7)	(3, 3, 5)	(5, 5, 7)	(5, 5, 7)	(5, 7, 7)	(5, 5, 7)

Next, the importance weights of the assessment criteria (resilience capabilities) were evaluated using the Improved Fuzzy Stepwise Weight Assessment Ratio Analysis (IMF-SWARA) method [69]. The inconsistency rate was maintained at less than 0.1, confirming the reliability of the expert judgments. The results of the IMF-SWARA calculations, including the fuzzy coefficients (k_j), calculated weights (q_j), final fuzzy weights (w_j), and defuzzified weight (x_{ij}), are presented in Table 7.

Table 7

Results of the calculation of the criterion value using the fuzzy PIPRECIA method.

	S_j	k_j	q_j	w_j	x_{ij}
C1	(0.5, 0.667, 1.)	(1.5, 1.667, 2)	(1, 1, 1)	(0.446, 0.465, 0.486)	0/466
C2	(0.667, 1, 1.5)	(1.667, 2, 2.5)	(0.4, 0.5, 0.6)	(0.178, 0.232, 0.292)	0/234
C3	(1, 1, 1)	(2, 2, 2)	(0.3, 0.25, 0.2)	(0.134, 0.116, 0.097)	0/116
C4	(0.4, 0.5, 0.667)	(1.4, 1.5, 1.667)	(0.12, 0.167, 0.214)	(0.054, 0.078, 0.104)	0/079
C5	(0.25, 0.286, 0.333)	(1.25, 1.286, 1.333)	(0.161, 0.13, 0.096)	(0.072, 0.06, 0.047)	0/06
C6	(0.222, 0.25, 0.286)	(1.222, 1.25, 1.286)	(0.075, 0.104, 0.132)	(0.033, 0.048, 0.064)	0/048

The order of importance for the resilience criteria from weight to lowest weight is as follows: C1 (Anticipation and Preparedness) with a weight of 0.466, C2 (Absorption and Response) with a weight of 0.234, C3 (Recovery and Adaptation) with a weight of 0.116, C4 (Collaboration and Visibility) with a weight of 0.079, C5 (Resources and Capacity Building) with a weight of 0.060 and C6 (Strategic and Structural Capabilities), with a weight of 0.048. Importantly, the proactive capabilities (Anticipation and Preparedness) were identified as the critical dimension receiving almost twice the weight of the reactive capabilities (Absorption and Response).

Subsequently, the digital maturity indicators (alternatives A1-A8) identified from the literature and expert input (see Table 2) were evaluated and prioritized using the Fuzzy Measurement Alternatives and Ranking according to the Compromise Solution (F-MARCOS) method [61]. The initial fuzzy decision matrix was constructed based on experts' linguistic assessments of the influence of each digital maturity indicator on each resilience criterion. This matrix was then extended with fuzzy ideal (ID) and anti-ideal (AI) solutions (see Table 6), normalized (see Table 8), and weighted using the criterion weights obtained from the IMF-SWARA method (see Table 9).

Table 8

Normalized fuzzy decision matrix

	C1	C2	C3	C4	C5	C6
A1	(0.777, 0.777, 1)	(0.555, 0.777, 0.777)	(0.777, 1, 1)	(0.777, 1, 1)	(0.555, 0.777, 0.777)	(0.777, 1, 1)
A2	(0.555, 0.555, 0.777)	(0.777, 0.777, 1)	(0.777, 0.777, 1)	(0.777, 0.777, 1)	(0.555, 0.555, 0.777)	(0.777, 0.777, 1)
A3	(0.333, 0.555, 0.555)	(0.555, 0.555, 0.777)	(0.555, 0.555, 0.777)	(0.555, 0.777, 0.777)	(0.333, 0.555, 0.555)	(0.777, 0.777, 1)
A4	(0.333, 0.555, 0.555)	(0.555, 0.777, 0.777)	(0.555, 0.777, 0.777)	(0.555, 0.555, 0.555)	(0.555, 0.777, 0.777)	(0.555, 0.777, 0.777)
A5	(0.555, 0.777, 0.777)	(0.555, 0.777, 0.777)	(0.555, 0.555, 0.777)	(0.333, 0.555, 0.555)	(0.777, 0.777, 1)	(0.555, 0.555, 0.777)
A6	(0.555, 0.555, 0.777)	(0.777, 0.777, 1)	(0.555, 0.555, 0.777)	(0.555, 0.555, 0.777)	(0.333, 0.555, 0.555)	(0.555, 0.777, 0.777)
A7	(0.777, 0.777, 1)	(0.333, 0.555, 0.555)	(0.555, 0.777, 0.777)	(0.777, 0.777, 1)	(0.777, 0.777, 1)	(0.777, 0.777, 1)
A8	(0.555, 0.777, 0.777)	(0.333, 0.333, 0.555)	(0.555, 0.555, 0.777)	(0.555, 0.555, 0.777)	(0.555, 0.777, 0.777)	(0.555, 0.555, 0.777)

Table 9

Weighted normalized fuzzy decision matrix

	C1	C2	C3	C4	C5	C6
A1	(0.347, 0.31, 0.486)	(0.099, 0.18, 0.227)	(0.104, 0.116, 0.097)	(0.042, 0.078, 0.104)	(0.040, 0.046, 0.036)	(0.026, 0.048, 0.064)
A2	(0.247, 0.259, 0.377)	(0.138, 0.180, 0.292)	(0.104, 0.09, 0.097)	(0.041, 0.06, 0.104)	(0.04, 0.033, 0.036)	(0.025, 0.037, 0.064)
A3	(0.148, 0.258, 0.270)	(0.099, 0.1288, 0.227)	(0.074, 0.064, 0.075)	(0.030, 0.060, 0.08)	(0.024, 0.033, 0.026)	(0.025, 0.037, 0.064)
A4	(0.148, 0.258, 0.27)	(0.099, 0.18, 0.226)	(0.074, 0.09, 0.075)	(0.030, 0.432, 0.058)	(0.04, 0.046, 0.036)	(0.018, 0.037, 0.05)
A5	(0.247, 0.361, 0.377)	(0.099, 0.180, 0.227)	(0.074, 0.064, 0.075)	(0.018, 0.043, 0.057)	(0.056, 0.046, 0.047)	(0.018, 0.043, 0.057)
A6	(0.247, 0.258, 0.377)	(0.138, 0.18, 0.292)	(0.074, 0.064, 0.075)	(0.03, 0.043, 0.08)	(0.024, 0.033, 0.026)	(0.018, 0.037, 0.05)
A7	(0.346, 0.361, 0.486)	(0.058, 0.129, 0.162)	(0.07, 0.09, 0.075)	(0.042, 0.06, 0.104)	(0.055, 0.046, 0.047)	(0.025, 0.037, 0.064)
A8	(0.247, 0.361, 0.377)	(0.059, 0.077, 0.162)	(0.074, 0.064, 0.075)	(0.03, 0.043, 0.08)	(0.040, 0.046, 0.036)	(0.018, 0.026, 0.05)

The final utility functions and the overall utility values (K_i) for each digital maturity indicator were calculated (see Table 10). In this study, the prioritization of digital maturity indicators based on their overall impact on enhancing resilience capabilities is as follows: A1 (Strategic Leadership and Governance) is ranked first with the highest utility value ($K_i = 0.769$), A2 (Workforce and Technology Integration) is second ($K_i = 0.637$), A7 (Customer and Experience) is third ($K_i = 0.588$), A5 (Technology Deployment) is fourth ($K_i = 0.529$), A6 (Data-Driven Intelligence and Insights) is fifth ($K_i = 0.513$), A4 (Automation) is sixth ($K_i = 0.416$), A8 (Healthcare-Specific Digital Solutions) is seventh ($K_i = 0.394$), and A3 (Integrated Digital Operations) is ranked last ($K_i = 0.372$) (see Table 10).

Table 10

Calculation of the next two steps and results of the applied fuzzy MARCOS

	$f(\tilde{K}_i^-)$	$f(\tilde{K}_i^+)$	K-	k+	f(K-)	f(K+)	Ki	Rank
A1	(0/419, 0/419, 0/419)	(0/607, 0/572, 0/595)	1/388	1	0/419	0/582	0/769	1
A2	(0/373, 0/385, 0/402)	(0/54, 0/526, 0/571)	1/279	0/921	0/386	0/536	0/637	2
A3	(0/289, 0/307, 0/308)	(0/419, 0/419, 0/438)	1/008	0/726	0/304	0/422	0/372	8
A4	(0/302, 0/322, 0/327)	(0/438, 0/439, 0/464)	1/059	0/763	0/32	0/443	0/416	6
A5	(0/351, 0/359, 0/347)	(0/508, 0/49, 0/493)	1/179	0/85	0/356	0/494	0/529	4
A6	(0/343, 0/35, 0/361)	(0/497, 0/478, 0/512)	1/163	0/838	0/351	0/487	0/513	5
A7	(0/379, 0/373, 0/364)	(0/55, 0/509, 0/517)	1/236	0/89	0/373	0/517	0/588	3
A8	(0/313, 0/316, 0/295)	(0/454, 0/431, 0/419)	1/033	0/744	0/312	0/433	0/394	7

Tables 6, 7, 8, 9, and 10 demonstrate the step-by-step computational process of the F-MARCOS method, including the extended initial fuzzy matrix, normalized fuzzy matrix, weighted normalized fuzzy matrix, and the final utility functions. Digital maturity indicators ranked in the top tier (A1, A2, A7) exhibit the greatest driving power and influence on resilience capabilities, while those in the lower tier (A3, A8) demonstrate more dependence and are considered supporting or foundational indicators. The results indicate that A1 (Strategic Leadership and Governance), encompassing strategy development, leadership support, financial investment, and cybersecurity governance, is the most critical digital enabler for building resilient healthcare supply chains. Conversely, A3 (Integrated Digital Operations), which primarily focuses on horizontal and vertical integration and ecosystem collaboration, shows the lowest utility value, suggesting that while it is a foundational capability, it may have less direct impact on resilience when considered in isolation from strategic and human-centric factors.

4. Conclusion

In this study, resilience capabilities of digital healthcare supply chains in the pharmaceutical industry are prioritized using a hybrid method that incorporates Improved Fuzzy Stepwise Weight Assessment Ratio Analysis (IMF-SWARA) and Fuzzy Measurement Alternatives and Ranking according to the Compromise Solution (F-MARCOS). Data are gathered from seven experienced professionals in the healthcare supply chain field via structured questionnaires to determine evaluation criteria weights and assess the influence of digital maturity indicators on resilience capabilities. Qualitative opinions of experts are transformed into triangular fuzzy numbers (TFNs) as input information for the IMF-SWARA and F-MARCOS methods for criteria weighting and alternative prioritization, respectively. The obtained results emphasize that Anticipation and Preparedness (C1) with a weight of 0.466, Absorption and Response (C2) with 0.234, and Recovery and Adaptation (C3) with 0.116 are the most important factors for prioritizing resilience capabilities in digital healthcare supply chains. Strategic Leadership and Governance (A1), Workforce and Technology Integration (A2), and

Customer and Experience (A7) have the highest importance in this study for enhancing resilience capabilities through digitalization, with utility values of 0.769, 0.637, and 0.588, respectively. The digital maturity indicators are sorted with the F-MARCOS method, looking at how much each one helps make the system more resilient. The results show that A1- Strategic Leadership and Governance is the digital maturity indicator. Next comes A2- Workforce and Technology Integration as the digital maturity indicator.

The third digital maturity indicator is A7- Customer and Experience. A5- Technology Deployment comes in fourth with a utility value of 0.529. A6- Data-Driven Intelligence and Insights is fifth with 0.513. A4- Automation is sixth with 0.416. A8- Healthcare-Specific Digital Solutions is seventh with 0.394. The last digital maturity indicator is A3- Integrated Digital Operations, with a utility value of 0.372. The digital maturity indicators that are in the tiers A1, A2, and A7 have the strongest influence on resilience. The digital maturity indicators that are in the tier A3, A8 are more dependent and act as support or foundation. These findings give ideas for people who run healthcare supply chains and for those who make rules. First, the fact that Anticipation and Preparedness is the critical resilience capability means that healthcare organizations should put money into tools that can predict problems, track things in real time, and plan ahead to stop disruptions before they happen. Second, the fact that Strategic Leadership and Governance is a powerful digital maturity indicator means that big changes in technology should come from the top, with leaders who are committed enough to invest money and set strict rules for cybersecurity. Third, the high ranking of Workforce and Technology Integration shows that training people, giving them skills, and keeping them updated in digital tools is very important. For future research directions, using hybrid decision-making methods for handling complex relations between a large number of assessment criteria, such as fuzzy DEMATEL-based ANP (DNP) and Best-Worst Method (BWM), is proposed. Additionally, using new methods such as total interpretive structural modeling (TISM) is suggested for analyzing interrelationships between resilience capabilities and digital maturity indicators by focusing on 'why?' besides 'what?' and 'how?' aspects. Future studies could also extend this research to other healthcare sectors, such as medical devices or hospital supply chains, and across different geographical contexts to validate the findings. Moreover, applying the developed framework to assess the actual digital maturity levels of specific healthcare organizations and examining the causal relationships between digital maturity levels and resilience outcomes empirically would be a valuable direction for future research.

Authors' contributions

Conceptualization, M.D., M.R. and S.D. ; methodology, M.D and M.R.; software, M.R.; validation, M.D.; formal analysis, M.R.; investigation, M.D.; resources, M.D.; data curation, M.D.; writing—original draft preparation, M.D.; writing—review and editing, M.D. and S.D.; visualization, M.D.; supervision, A.H.; project administration, M.D. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

All authors declare that they have no conflict of interest.

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