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Evaluation of Critical Success Factors for Antifragile Supply Chains Using Delphi and Fuzzy QFD Methods

Ayça MADEN[1], Eren ÖZCEYLAN[2,3], Dilara MUHACIR[4], Beata MRUGALSKA[5]

[1] *Beykent University, Industrial Engineering Department, Türkiye*
[2] *Gaziantep University, Industrial Engineering Department, Türkiye*
[3] *Department of Technical Sciences, Western Caspian University, Baku, Azerbaijan*
[4] *BOYAR Kimya Company, R&D Department, Türkiye*
[5] *Poznan University of Technology, Faculty of Engineering Management*

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Abstract
The antifragile supply chain (ASC) provides a significant advantage compared to traditional systems, particularly when considering the impacts of unexpected crises such as COVID-19. Such challenging events highlight the value of the ASCs that enable businesses to navigate crises turn these challenges into opportunities, and continuously strengthen their structures. While resilience strategies gain attention, practical studies on ASCs are limited. This study applies a case study to examine critical success factors for ASCs, demonstrating the practical application of the Delphi and Fuzzy QFD method within Boyar Kimya, a textile manufacturer. By understanding the relationships between customer needs and critical success factors, the analysis contributes to determining and effectively implementing ASC strategies. The study concludes by unveiling key success factors, including SC risk management, information sharing, proactive management, efficient knowledge processes, collaboration, and innovation strategies. This research provides a valuable roadmap for enhancing SC efficiency and sustaining a competitive advantage.

Keywords
Antifragile supply chain; Delphi; Fuzzy QFD; Critical success factors; Supply chain risks.

Introduction

According to a study conducted by the National Association of Manufacturers (The National Association of Manufacturers, 2020), the COVID-19 pandemic has had a significant impact on 78% of manufacturing companies. The pandemic has likely provided valuable insights into identifying vulnerabilities, and these lessons could serve as a foundation for developing an antifragile supply chain (Nikookar et al., 2021). Following the publication of the book "Antifragile: Things That Gain from Disorder" (Taleb, 2012), there has been increased recognition of the applicability of resilience strategies to risk management (Bravo & Hernández, 2021). Taleb (2012) introduced the notion of 'antifragility' as a contrasting attribute to robustness. Antifragility characterizes systems that benefit from volatility and chaos, demonstrating enhanced performance when exposed to significant and seemingly unlikely variations in parameters (Größler, 2020). While antifragility includes the aspect of robustness, which entails recovering from shocks, it goes further by striving to achieve an even higher level of performance subsequent to such shocks (Größler, 2020). This emerging concept aims to endure extreme events without significantly affecting overall outcomes, fostering learning, adaptation, and the exploitation of opportunities to enhance performance and foster growth (Bravo & Hernández, 2021). In literature, there are few practical studies conducted on antifragile supply chains. While traditional resilient chains can merely withstand crises, antifragile chains have the capacity to turn changes into opportunities. Therefore, conducting in-depth examinations of antifragile supply chain applications and further research in this area can assist businesses in increasing their resilience and improving their ability to adapt to variable conditions. Examining the critical

Corresponding author: *E. Özceylan – Gaziantep Üniversitesi, Mühendislik Fakültesi, Endüstri Mühendisliği Bölümü, Gaziantep 27310, Türkiye, phone: (+90) 342 317 26 18, e-mail: erenozceylan@gmail.com*

success factors of antifragile success can be essential to understand, identify, and enhance organizations' resilience and development against external shocks. The necessary success factors for an antifragile supply chain must be addressed in conjunction with potential emerging requirements. This study focuses on conducting a case study to examine critical success factors for antifragile supply chains. It demonstrates the practical implementation of the Delphi and Fuzzy Quality Function Deployment (QFD) methods within the context of Boyar Kimya, a company in the textile industry. In this study, after identifying the needs of the case company, the critical success factors of antifragile supply chains were examined through the Delphi and Fuzzy QFD methods. This examination presents a strategic approach to enhance the company's sustainability, strengthen resilience against uncertainties, and operate successfully in variable market conditions. By utilizing the Fuzzy QFD method to understand the relationships between customer needs and company objectives, it can contribute to determining antifragile supply chain strategies and their effective implementation. This analysis can provide a valuable roadmap for increasing operational excellence and sustaining a competitive advantage for the company.

The structure of the paper is as follows: Section 2 provides a review of the literature. Section 3 details the methodology, Section 4 delineates the case study, and Section 5 explores discussion.

Literature review

Antifragility has recently gained significant prominence as a relatively new concept and is increasingly being utilized in various fields. Taleb (2012) introduced the concept of antifragility, which refers to the ability of a system to confront stressors, shocks, and volatility and not only survive but thrive in the face of them.

Antifragility defines systems that thrive in the presence of volatility and chaos, showcasing improved performance when subjected to substantial and seemingly improbable changes in parameters (Größler, 2020). In an antifragile system, the occurrence of extreme events actually leads to positive outcomes (Bravo & Hernández, 2021). The distribution of results emphasizes predominantly favourable large values, minimizing potential drawbacks while exposing the system to the potential for upside gains (Bravo & Hernández, 2021). Although these types of systems are uncommon and have not been extensively studied within the context of enterprises, the concept of antifragility introduces the notion of connecting variability, uncertainties, and stress-induced risk to both positive and negative risks associated with future behaviour and an enhancement in performance (Benaben et al., 2019; Bravo & Hernández, 2021). Ever since Taleb introduced the concept of antifragility (Taleb, 2012) as the opposite of fragility, this idea has sparked interest and innovation among both researchers and professionals (Nikookar et al., 2021). Its versatile applicability has been observed in various fields, including aerospace engineering (Jones, 2015), computer science (Brandon-Jones et al., 2014; Verhulsta, 2014), risk assessment (Aven, 2015), finance and banking (Taleb & Douady, 2013; White, 2013), manufacturing (Priyadarshini et al., 2022), supply chain management (Nikookar et al., 2021), as well as the management of large-scale projects.

Understanding the distinctions between supply chain agility and related concepts such as flexibility, leanness, adaptability, and resilience is crucial due to their similar meanings (Patel & Sambasivan, 2022). Agility and flexibility are nuanced concepts with multiple dimensions. Despite distinct differences, they are often used interchangeably due to their overlapping characteristics (Fayezi et al., 2017). Agility entails promptly responding to changes, whereas flexibility involves effectively addressing alterations (Gong & Janssen, 2012). Although they represent distinct strategies, certain scholars view flexibility as a precursor to agility, while others regard it as a facilitator of agility. Literature discussing the paradigms of agility and leanness asserts their distinction and positions agility as a progression beyond leanness (Patel & Sambasivan, 2022). Agility implies an organization's ability to promptly respond to volatile demand, whereas leanness emphasizes efficiency by achieving more with fewer resources (Patel & Sambasivan, 2022). In supply chain contexts, agility revolves around swiftly recognizing and adapting to shifting customer needs, while leanness centers on waste elimination (Carvalho et al., 2012; Patel & Sambasivan, 2022).

Through an extensive review of literature, it has been observed that researchers have primarily focused on supply chain agility, leaving a dearth of high-quality research on supply chain adaptability (Patel & Sambasivan, 2022). This lack of emphasis presents challenges for readers in distinguishing between agility and adaptability. According to Lee (2004), supply chain agility involves promptly responding to unexpected shifts in demand and supply, whereas adaptability entails adjusting supply chain tactics and operations to address structural changes in the business environment. Lee's argument suggests that adaptability serves as a means to achieve supply chain agility. Agility underscores the importance of quick response times, while adaptability highlights the innovation in response strategies (Patel & Sambasivan, 2022).

Supply chain agility and supply chain resilience possess distinct characteristics and operate through different mechanisms: while supply chain agility typically focuses on external factors, supply chain resilience tends to prioritize internal aspects (Delbufalo, 2022). Several shared themes exist between agility and resilience, including the capacity to enhance operational speed, the capability to scan the environment for anticipation, and the ability to adapt tactics and operations (flexibility) (Gligor et al., 2019). The main spotlight on resilience is on ensuring firms' sustained survival through their inherent resilience processes (Delbufalo, 2022; Gölgeci et al., 2020). In contrast, agility research predominantly examines how organizations strategically align themselves with the external environment (Delbufalo, 2022). Consequently, they entail different desired outcomes: supply chain agility aims to foster prosperity, whereas the primary goal of supply chain resilience is ensuring longevity or survival (Ali et al., 2017).

Evaluating resilient supply chain barriers is a fundamental step toward establishing an antifragile supply chain. It provides the insights and tools necessary to enhance the supply chain's resilience, responsiveness, and adaptability, which are essential characteristics for achieving antifragility in the face of disruptions and uncertainties. Researchers emphasize that the exploration of barriers offers dual benefits to managers (Agarwal et al., 2022). Firstly, it aids in mitigating the adverse impacts of these obstacles, and secondly, it enables the identification of capabilities that fortify resilience (Agarwal et al., 2022; Rajesh, 2018). Consequently, comprehending and managing potential barriers becomes imperative for the attainment of the fundamental objective of achieving resilience. Rajesh, (2018), Ali and Gölgeci (2019), along with Golgeci and Kuivalainen (2020), contend that the predominant focus of resilience studies has been on the facilitators of supply chain resilience (Agarwal et al., 2022). However, there exists a need to delve into factors that might impede or hinder resilience, potentially jeopardizing firms' long-term viability (Agarwal et al., 2022). The exploration of these often overlooked negative factors has the potential to enrich our understanding of resilience by introducing new perspectives aimed at either diminishing the magnitude of these barriers or identifying capabilities that counterbalance their effects (Agarwal et al., 2022; Rajesh, 2018).

Numerous studies in existing literature have examined the influence of catastrophes and pandemics on the supply chain (Okorie et al., 2020; Priyadarshini et al., 2022; Sharma et al., 2020). Some have proposed resilience and robustness as strategies to address supply chain disturbances (Priyadarshini et al., 2022). However, the concept of resilience primarily focuses on the recovery of supply chains, overlooking the importance of deriving lessons and advancement from such disruptions (Priyadarshini et al., 2022). Therefore, the current imperative lies in establishing a supply chain that goes beyond resilience – one that can be termed as "antifragile" (Priyadarshini et al., 2022). While a resilient supply chain aims to absorb shocks, an antifragile supply chain views these shocks as prospects for enhancement and reinforcement (Priyadarshini et al., 2022). An antifragile supply chain not only reacts to disruptions but also prospers within them (Taleb, 2012). In the literature, studies conducted on the antifragile supply chain are quite limited. There are various studies that examine topics related to supply chain resilience using different Multiple Criteria Decision Making (MCDM) methods. For example, Nikookar et al. (2014) proposed a qualitative approach for resiliency in supply chains. Ajalli et al. (2021) evaluated the resilient suppliers with the combination of decision-making techniques. Liu et al., (2023) evaluated the enablers for maritime supplier chain resilience during the pandemic using an integrated methodology that combines Interpretive Structural Modelling (ISM), fuzzy Matriced Impacts Croisés Multiplication Appliquée á un Classement (MICMAC), and Decision-Making Trial and Evaluation Laboratory (DEMATEL). Sun et al. (2023) integrates quality function deployment (QFD) and intuitionistic fuzzy set (IFS) to create an integrated approach for the effective formulation of resilient strategies for bauxite maritime supply chain design. The methodology considers both customer requirements and risk factors. Boz et al., (2022) proposed an MCDM approach for sustainable supplier selection in healthcare system using the fuzzy Best-Worst Method (F-BWM) and the fuzzy Additive Ratio Assessment Method (F-ARAS). Hsu et al. (2021) aimed to improve supply chain agility with industry 4.0 enablers to mitigate ripple effects using an integrated QFD-MCDM approach. Nazari-Shirkouhi et al. (2023) proposed an integrated approach by using Z-number DEA model and artificial Neural Network for resilient supplier selection. Mohammed et al. (2019) proposed a hybrid MCDM-fuzzy multi-objective programming approach for a green and resilient supply chain network design. Hsu et al. (2022) aimed to deploy Big Data enablers to strengthen supply chain resilience to decrease sustainable risks using an integrated House of Quality-MCDM approach.

Rehman and Ali (2022) aim to prioritize resilience strategies for healthcare supply chains using Fuzzy AHP, TOPSIS, and QFD. In a survey conducted by Halkos et al. (2018), the impact of barriers on supply chain resilience was examined through the application of Structural Equation Modelling. Rajesh (2018) employed the grey-clustering and VIKOR methodology to rank the barriers affecting resilience in the electronics supply chain. While there have been studies on resilient supply chains in the literature, there are almost no practical studies conducted on antifragile supply chains. Hence, thorough investigations into the practical implementations of antifragile supply chains and additional exploration in this domain can aid supply chains in enhancing their resilience and bolstering their capacity to adjust to fluctuating circumstances. In this study, Fuzzy QFD method was employed to investigate the critical success factors of antifragile supply chains for a company. This study can play a crucial role in identifying strategies for antifragile supply chains and ensuring their successful implementation.

Materials and methods

The steps of the methodology are: collection of the problems from the case company, determination of the critical success factors from literature for antifragile supply chains, focusing on the important success factors using the Delphi method, and determination of them as technical attribute part of the QFD, calculation of the weights of the customer requirements part of the QFD, calculation of the relations between customer requirements and the critical success factors, and determination of the weights of technical attributes part of the QFD (critical success factors) by multiplying the weights of the customer requirements with the weights of the relations. The steps implemented in this study are illustrated in Fig. 1.

In this study, the aggregation of three fuzzy numbers was achieved using the arithmetic mean, and the process of defuzzification employed the Centroid method. Various methods exist for defuzzifying a fuzzy number into a precise value, such as the Mean of Maximum and the Centroid method, also recognized as the Center of Gravity or Center of Area method (Hanss, 2005). The Centroid method is often preferred for its simplicity. In this investigation, the defuzzification of a Triangular Fuzzy Number (TFN) $= (l, m, u)$ utilized the Centroid method. The calculation of the centroid method involves the following formula,

$$Centroid\left(\tilde{A}\right) = \frac{l+m+u}{3}. \tag{1}$$

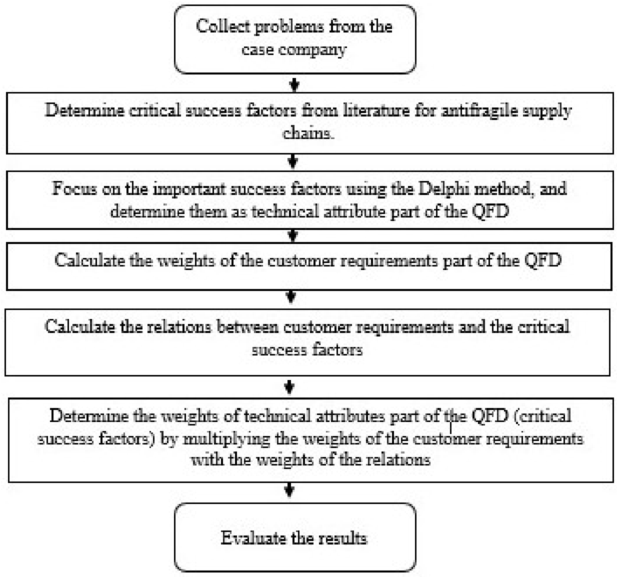

Fig. 1. Steps of the applied methodology

Linguistic terms used can be seen in Table 1.

Table 1
Linguistic term set (Bevilacqua et al., 2006)

Linguistic values	TFN
Very low (VL)	(0, 1, 2)
Low (L)	(2, 3, 4)
Medium (M)	(4, 5, 6)
High (H)	(6, 7, 8)
Very high (VH)	(8, 9, 10)

Delphi method

The Delphi method is utilized to systematically gather and refine the opinions of experts regarding the subject under investigation until a consensus is achieved among their perspectives (Emovon et al., 2018). This technique facilitates the collection and refinement of expert judgments through continuous data gathering and additional brainstorming sessions focused on the topic in question. The Consistency Validity Ratio (CVR) is determined using the formula

$$\mathrm{CVR} = \frac{\mathrm{NPE} - \frac{N}{2}}{\frac{N}{2}}. \tag{2}$$

In this formula, CVR represents the Consistency Validity Ratio, NPE indicates the Number of experts identifying the criteria as essential, and N represents the Total number of Experts. The threshold value for CVR is established at 0.29 (Dohale et al., 2021; Emovon et al., 2018). Any criterion with a CVR value of 0.29 or higher is retained, while the remaining criteria are discarded.

Fuzzy QFD

The primary objective of a House of Quality (HOQ) is to determine the relative importance weights of design requirements based on the significance ratings assigned to customer needs and the interconnections between customer requirements and design specifications (Temponi et al., 1999). This approach has been commonly employed in various sectors such as software systems, production, supply chain, service, and communication (Çevik Onar et al., 2016; Haktanır & Kahraman, 2019).

QFD offers several benefits, including enhanced customer satisfaction, potential for ground-breaking innovation, reduced manufacturing costs, shorter lead times, improved communication through collaborative cross-functional teams, and knowledge preservation (Liu & Wang, 2010). Its competitive edge lies in its structured integration of strategic concepts (Brown, 1991). Safeguarding the input from customers ensures that their requirements remain unaltered during the development phase. This ensures that the voice of the customer is upheld within the design features. The term "product" encompasses any process output intended for consumption, representing both services and tangible goods (Brown, 1991). Consequently, this approach brings the interests of marketing, design, deployment, and support functions to the forefront, addressing them early in the process (Brown, 1991). The cross-functional team members contribute specialized knowledge about their respective capabilities and needs to their organizations.

In the traditional QFD process, the customer rating and relationship rating in the HOQ are typically represented using a point system like 1–3–5 or 1–5–9. These numbers correspond to qualitative judgments such as "weak," "moderate," and "strong." However, when human decisions lack precision, fuzzy set theory is introduced as an appropriate method to convert these judgments into numerical values (Liu, 2009). In the scope of this study on Fuzzy QFD, TFNs have been utilized.

Case study

In this study, a company from the textile industry has been selected for practical implementation. The case company, Boyar Kimya, is located in the province of Gaziantep in Turkey. Born half a century ago in the realm of yarn and dye, the case company leads the industry by elevating its high standards to an international quality framework. Upholding its values, it continues its production with a sustainable goal. However, the recent earthquake and pandemic have adversely affected the company's supply chain processes. In the face of these unforeseen circumstances such as earthquakes and pandemics, it is imperative for the company to take necessary actions promptly, implementing measures to address and mitigate the challenges posed by these unexpected events. Despite Boyar Kimya's longstanding presence and reputation in the textile industry, recent disruptions from earthquakes and the pandemic have exposed vulnerabilities in its supply chain resilience. While the company has historically upheld high standards and pursued sustainable production practices, these unforeseen events have underscored the need for a more comprehensive approach to risk management and contingency planning. To truly thrive amidst chaos, Boyar Kimya must delve deeper into its organizational structure, operational processes, and strategic decision-making frameworks. By conducting a thorough analysis of these aspects, the company can identify areas for improvement and develop robust strategies to enhance its antifragility in the future.

In recent years, the complex challenges and sudden changes encountered have significantly impacted the company's sustainability. To overcome these challenges, Boyar Kimya has opted to embrace the concept of antifragility and transform its supply chain accordingly. The company's endeavors to address these challenges and bolster antifragility aim not only to surpass ordinary supply chain resilience but also to excel in chaotic environments. Therefore, by conducting an antifragility-focused study, the company seeks to fortify its supply chain, making it more resilient, flexible, and adaptable to better navigate future uncertainties.

The company finds that its goals often clash with those of its suppliers and distributors. For instance, while the company prioritizes timely delivery and product quality, its suppliers may focus solely on cost reduction. This misalignment leads to inefficiencies and hampers the company's ability to respond quickly to market demands. The company's supply chain spans multiple tiers of suppliers, manufacturers, and distributors across different regions. This intricate network increases the risk of disruptions due to factors such as transportation delays or regulatory changes. Managing this complexity becomes challenging, making the company more susceptible to unexpected events.

The company faces a pervasive issue of distrust among its supply chain partners. Despite being reliant on each other for success, there's a lack of confidence in capabilities and intentions. This lack of trust impedes collaboration and undermines the company's ability to coordinate responses to market fluctuations effectively. Communication breakdowns between frontline employees and management hinder the company's ability to relay crucial information to decision-makers. Without clear communication channels, management remains unaware of operational challenges and opportunities, leading to suboptimal decision-making.

The company struggles with fragmented IT systems across its supply chain partners. This lack of integration results in data silos and communication barriers, hindering real-time information sharing and collaboration. As a result, the company faces difficulties in streamlining processes and responding swiftly to changes in demand or supply. The company finds itself unprepared for unexpected disruptions in its supply chain. Without robust contingency plans in place, the company is vulnerable to risks such as supplier bankruptcies or natural disasters. This lack of preparedness amplifies the impact of disruptions and prolongs recovery efforts. Despite the potential benefits, the company struggles to adopt cutting-edge technologies within its operations. The absence of Industry 4.0 innovations like IoT or AI hampers the company's ability to optimize processes and enhance supply chain visibility. As a result, the company lags behind competitors in efficiency and responsiveness.

Limited financial resources constrain the company's ability to invest in resilience-building initiatives. Without adequate funding, the company struggles to implement risk mitigation measures or upgrade its infrastructure. This financial constraint exposes the company to heightened risks and limits its capacity for growth and innovation. The company's decision-making processes are rigid and hierarchical, hindering agility and innovation. Frontline employees lack the autonomy to make timely decisions, resulting in delays and missed opportunities. This lack of flexibility undermines the company's ability to adapt to changing market dynamics and capitalize on emerging trends. The company's critical assets, such as manufacturing facilities and distribution centers, are concentrated in a few locations. This centralized approach increases vulnerability to localized disruptions, posing significant risks to the company's supply chain resilience. Diversifying asset locations becomes imperative to mitigate these risks and ensure business continuity. The established problems are presented as outlined in Table 2.

Table 2
Determined problems of the case company

Problems
Conflicting objectives with supply chain partners
Extensive network complexity
Insufficient faith and lack of trust among members of supply chain
Lack of communication with superiors
Lack of IT integration among partners
Lack of contingency plans
Unavailability of latest industry 4.0 technologies
Financial constraints
Non-existence of flexible decision-making systems
Centralization of assets

Challenges within the company and disruptions in its supply chain prompt an in-depth investigation to steer the company towards more effectively managed objectives. To address these challenges systematically, the company sought to employ Fuzzy QFD to evaluate and prioritize these customer requirements, aiming to transform these obstacles into opportunities for growth and innovation. The identified problems within the case company were addressed by incorporating perspectives from experts within the company. A committee consisting of three experts with substantial backgrounds within the case company, each boasting more than five years of expertise, conducted the evaluation. This committee comprises two specialists in manufacturing and one manager in supply chain management, all possessing the requisite knowledge in manufacturing processes and resilient supply chains.

The determined problems are as follows: conflicting objectives with supply chain partners (CR1), extensive network complexity (CR2), insufficient faith and lack of trust among members of supply chain (CR3), lack of communication with superiors (CR4), lack of IT integration among partners (CR5), lack of contingency plans (CR6), unavailability of latest industry 4.0 technologies (CR7), Financial constraints (CR8), non-existence of flexible decision-making systems (CR9), and centralization of assets (CR10). After the problems were identified, the weights of customer needs were aggregated using linguistic expressions in Table 1. Aggregated importance of the customer requirements can be seen in Table 3.

As antifragile supply chain is still a new topic, the number of studies focusing on this topic, especially on determining the critical success factors, is quite limited. Therefore, this study particularly focuses on the comprehensive study conducted by (Priyadarshini

Table 3
Aggregated importance of the customer requirements

Customer requirements	Importance
CR1	H
CR2	M
CR3	M
CR4	VH
CR5	VH
CR6	VH
CR7	M
CR8	M
CR9	VH
CR10	L

et al., 2022) for critical success factors. The critical success factors to build an antifragile supply chain have been identified as shown in Table 4.

Table 4
Critical success factors to build an antifragile supply chain (Priyadarshini et al., 2022)

Critical success factors
Development of skilled workforce
Cost-effective design and manufacturing
Reduction in manufacturing lead-times
Development of a strategy for collaboration and innovation
Supply chain risk management
Effective inventory management
Proactive top management
Efficient information sharing process
Distributed manufacturing system
Resource allocation for digitalization
Rapid market responsiveness
Integrated manufacturing processes/operations
Effective knowledge management process
Design freedom and customisability
Environmental sustainability
Supply chain redesigns
Manufacturing repurposing
Effective additive manufacturing processes
Antifragile supply chain

Out of these 19 critical success factors, 16 were chosen by incorporating insights from expert perspectives using the Delphi method. The CVR scores for the attributes selected via the Delphi method are represented in Table 5.

The identified 16 factors are as follows: development of skilled workforce (TA1), cost-effective design and manufacturing (TA2), reduction in manufacturing lead-times (TA3), development of a strategy for collaboration and innovation (TA4), supply chain risk management (TA5), effective inventory management (TA6), proactive top management (TA7), efficient information sharing process (TA8), distributed manufacturing system (TA9), resource allocation for digitalization (TA10), rapid market responsiveness (TA11), integrated manufacturing processes/operations (TA12), effective knowledge management process (TA13), design freedom and customisability (TA14), environmental sustainability (TA15), and supply chain redesigns (TA16). The linguistic expressions determined by the three experts for the relations between customer requirements and technical attributes are as shown in Tables 6, 7, and 8 below. Values in Tables 6, 7, and 8 were aggregated using the arithmetic mean. Aggregated relations between customers' requirements and technical attributes can be seen in Table 9.

Table 5
The CVR scores for the attributes selected via the Delphi method

Technical attributes	CVR value
Development of skilled workforce	0.333
Cost-effective design and manufacturing	1.000
Reduction in manufacturing lead-times	1.000
Development of a strategy for collaboration and innovation	1.000
Supply chain risk management	0.333
Effective inventory management	1.000
Proactive top management	0.333
Efficient information sharing process	0.333
Distributed manufacturing system	0.333
Resource allocation for digitalization	1.000
Rapid market responsiveness	0.333
Integrated manufacturing processes/operations	1.000
Effective knowledge management process	1.000
Design freedom and customisability	1.000
Environmental sustainability	0.333
Supply chain redesigns	1.000

Fuzzy values from the QFD relations section and customer requirements section were multiplied with each other, resulting in the fuzzy and crisp values in Table 10 as follows.

Defuzzified importance values, ranked from highest to lowest, for the TAs are as follows: TA5 (40.667), TA8 (40.667), TA7 (40.067), TA13 (39.867),

Table 6
Evaluations of the relations between CRs and TAs by the first experts

	TA1	TA2	TA3	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14	TA15	TA16
CR1	L	L	VL	L	M	L	M	M	L	L	L	M	M	L	L	L
CR2	M	M	M	M	M	M	L	L	L	M	L	M	M	L	L	L
CR3	L	L	L	L	L	VL	M	M	L	M	L	L	M	L	VL	L
CR4	L	L	M	M	L	L	M	M	VL	L	L	L	M	M	L	L
CR5	L	M	L	M	M	M	M	L	VL	L	VL	L	M	L	L	L
CR6	M	VL	L	L	L	VL	VL	L	L	L	VL	VL	VL	L	L	L
CR7	M	L	M	VL	L	L	L	L	L	VL	VL	L	L	L	L	M
CR8	M	M	M	M	M	M	M	M	L	L	M	L	M	L	M	M
CR9	L	L	L	L	M	M	M	M	L	L	L	L	L	M	L	L
CR10	VL	VL	L	L	L	L	VL	L	L	VL	M	M	L	M	M	M

Table 7
Evaluations of the relations between CRs and TAs by the second experts

	TA1	TA2	TA3	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14	TA15	TA16
CR1	M	M	L	M	H	M	H	H	M	M	M	H	H	M	M	M
CR2	H	H	H	H	H	H	M	M	M	H	M	H	H	M	M	M
CR3	M	M	M	M	M	L	H	H	M	H	M	M	H	M	L	M
CR4	M	M	H	H	M	M	H	H	L	M	M	M	H	H	M	M
CR5	M	H	M	H	H	H	H	M	L	M	L	M	H	M	M	M
CR6	H	L	M	M	M	L	L	M	M	M	L	L	L	M	M	M
CR7	H	M	H	L	M	M	M	M	M	L	L	M	M	M	M	H
CR8	H	H	H	H	H	H	H	H	M	M	H	M	H	M	H	H
CR9	M	M	M	M	H	H	H	H	M	M	M	M	M	H	M	M
CR10	L	L	M	M	M	M	L	M	M	L	H	H	M	H	H	H

Table 8
Evaluations of the relations between CRs and TAs by the third experts

	TA1	TA2	TA3	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14	TA15	TA16
CR1	H	H	M	H	VH	H	VH	VH	H	H	H	VH	VH	H	H	H
CR2	VH	VH	VH	VH	VH	VH	H	H	H	VH	H	VH	VH	H	H	H
CR3	H	H	H	H	H	M	VH	VH	H	VH	H	H	VH	H	M	H
CR4	H	H	VH	VH	H	H	VH	VH	M	H	H	H	VH	VH	H	H
CR5	H	VH	H	VH	VH	VH	VH	H	M	H	M	H	VH	H	H	H
CR6	VH	M	H	H	H	M	M	H	H	H	M	M	M	H	H	H
CR7	VH	H	VH	M	H	H	H	H	H	M	M	H	H	H	H	VH
CR8	VH	VH	VH	VH	VH	VH	VH	VH	H	H	VH	H	VH	H	VH	VH
CR9	H	H	H	H	VH	VH	VH	VH	H	H	H	H	H	VH	H	H
CR10	M	M	H	H	H	H	M	H	H	M	VH	VH	H	VH	VH	VH

TA4 (38.267), TA14 (37.867), TA1 (37.867), TA3 (37.067), TA6 (36.467), TA16 (36.267), TA2 (35.067), TA12 (34.867), TA15 (34.267), TA10 (34.067), TA11 (30.667), and TA9 (30.067). Considering the results, it can be observed that the top 5 critical antifragile supply chain success factors, in order, are supply chain risk management, efficient information sharing process, proactive top management, effective knowledge

Table 9
Aggregated relations between customers' requirements and technical attributes

	TA1	TA2	TA3	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14	TA15	TA16
CR1	M	M	L	M	H	M	H	H	M	M	M	H	H	M	M	M
CR2	H	H	H	H	H	H	M	M	M	H	M	H	H	M	M	M
CR3	M	M	M	M	M	L	H	H	M	H	M	M	H	M	L	M
CR4	M	M	H	H	M	M	H	H	L	M	M	M	H	H	M	M
CR5	M	H	M	H	H	H	H	M	L	M	L	M	H	M	M	M
CR6	H	L	M	M	M	L	L	M	M	M	L	L	L	M	M	M
CR7	H	M	H	L	M	M	M	M	M	L	L	M	M	M	M	H
CR8	H	H	H	H	H	H	H	H	M	M	H	M	H	M	H	H
CR9	M	M	M	M	H	H	H	H	M	M	M	M	M	H	M	M
CR10	L	L	M	M	M	M	L	M	M	L	H	H	M	H	H	H

Table 10
Fuzzy evaluations of the technical attributes

Technical attributes	Fuzzy importance degree	Defuzzified importance
TA1	(26, 37.2, 50.4)	37.867
TA2	(23.6, 34.4, 47.2)	35.067
TA3	(25.2, 36.4, 49.6)	37.067
TA4	(26.4, 37.6, 50.8)	38.267
TA5	(28.4, 40, 53.6)	40.667
TA6	(24.8, 35.8, 48.8)	36.467
TA7	(28, 39.4, 52.8)	40.067
TA8	(28.4, 40, 53.6)	40.667
TA9	(19.2, 29.4, 41.6)	30.067
TA10	(22.8, 33.4, 46)	34.067
TA11	(19.6, 30, 42.4)	30.667
TA12	(23.2, 34.2, 47.2)	34.867
TA13	(27.6, 39.2, 52.8)	39.867
TA14	(26, 37.2, 50.4)	37.867
TA15	(22.8, 33.6, 46.4)	34.267
TA16	(24.4, 35.6, 48.8)	36.267

management process, and development of a strategy for collaboration and innovation. In light of the top 5 critical antifragile supply chain success factors identified at the conclusion of the study, it is recommended to develop different strategies within the company. The company should concentrate on strategies for managing supply chain risks within its activities pertaining to four interlinked processes: identifying, assessing, mitigating, and controlling risks. The sharing of information has a beneficial effect on enhancing the visibility of the supply chain, subsequently influencing its resilience. The substantial amount of information can be analyzed and leveraged for process enhancements, facilitated by increased levels of digitization within the company. Within the company, improving a proactive top-management strategy may allow for better anticipation of global crises, ultimately leading to enhanced competitiveness. Participating in vertical collaborations, such as partnerships between different companies, or horizontal collaborations, including cooperation within the company and partnerships with the government, can help the firm respond rapidly to global disruptions such as the COVID-19 pandemic. Close collaboration with government agencies and international organizations can streamline the coordination of emergency assistance to support the recovery of its supply chain from such disruptions. In addition, adoption of technological and operational innovations can assist the company in gaining a competitive edge and adapting to swift shifts in demand. Investing in information and communication technologies, including blockchain technology and digital technologies, allows the company to enhance the visibility and transparency of its supply chain. A comprehensive understanding of supply chain inventories and parameters is crucial to fortify supply chain resilience against information disruptions. Ensuring transparency in upstream and downstream inventories, demand, and supply chain conditions, as well as production and purchasing schedules is vital for bolstering the company's resilience to disruptions. The integration of digital data-driven supply chains, big data, the Internet of Things, data analytics, and blockchains may enhance supply chain resilience, enabling manufacturers within the company to receive accurate and timely information, and facilitating efficient recovery from disruptions.

Conclusions

Antifragile supply chains stand out by their ability to cope with variability and uncertainty, enhancing the resilience of businesses and providing a competitive advantage. In this research, a textile industry company has been chosen for practical application. Having originated in these textile realms, the selected case company has emerged as an industry leader, aligning its elevated standards with international quality frameworks. Committed to sustainability, the company persists in its production endeavours while facing challenges and disruptions in its supply chain. This research conducts a case study to explore the critical success factors associated with antifragile supply chains. It illustrates how the Delphi and Fuzzy QFD methods are practically applied within the realm of Boyar Kimya, a textile industry firm, to address this issue. Employing the Fuzzy QFD method to comprehend the relationships between customer needs and critical success factors for antifragile supply chains contribute to determining effective antifragile supply chain strategies and their implementation. Examining the outcomes reveals that the primary antifragile supply chain success factors, ranked in sequence, include supply chain risk management, an effective information sharing process, proactive top management, efficient knowledge management processes, and the formulation of a strategy for collaboration and innovation.

The study emphasizes the importance of dynamic risk management practices that enable organizations to anticipate, assess, and mitigate risks in real-time. Companies can implement agile risk management frameworks that continuously monitor and adapt to emerging threats, ensuring resilience in the face of uncertainty. Organizations can establish agile collaboration platforms and ecosystems that facilitate seamless information exchange, joint decision-making, and resource-sharing to respond swiftly to market changes and customer needs. Leaders can champion agile principles and practices, empower teams to make autonomous decisions, and create a supportive environment that encourages agility, adaptability, and resilience in the face of uncertainty. Companies can cultivate a culture of innovation, creativity, and continuous improvement to drive agility throughout the organization.

As this study focuses on a single case study application, its generalizability may be limited. Examining only one company could constrain the generalizability of the findings. However, future research could further evaluate the accuracy and generalizability of the results by implementing similar methods in different sectors and companies. Additionally, for future research, structural analysis will be conducted to examine the relationships among critical success factors of antifragile supply chains, utilizing the MICMAC software for factor grouping.

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