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Enhancing Strategic Management for Resilient Supply Chains in Construction Industry 4.0: A Fuzzy EDAS Methodology

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Abstract

Strategic management of one of the most complex and profitable supply chains necessitates the creation of transient and repeatable competitive advantages. The escalating disruptions in such supply chains underscore the criticality of resilience strategies for construction firms. By simultaneously considering all influencing variables, three primary criteria, human capital, technological development, and supply chain capabilities, along with fourteen sub-criteria, were identified. To prioritize these under the ambiguous and uncertain conditions of the real world, the Fuzzy EDAS technique was employed. The results highlight the primacy of human resources over technology, despite the latter being a hallmark of Industry 4.0. This intriguing paradox underscores the pivotal role of managers and employees, and their capabilities, in fostering supply chain resilience, followed by the integration of Industry 4.0 technologies.

Keywords: Resilient supply chain, Fuzzy EDAS, Construction supply chain, Industry 4.0.

1 | Introduction

The diversity, frequency, and intensity of supply chain disruptions have spurred a reimagination of supply chain management, emphasizing the adoption of resilience [1]. Black swan events such as the COVID-19 pandemic, geopolitical risks, and Iran-specific market conditions—including sanctions, inflation, fluctuations in international currency exchange rates, environmental uncertainty, and instability—have driven the traditionally linear and conventional supply chain management in the construction industry toward embracing

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resilience-oriented approaches [2]. Consequently, there is a pressing need to integrate concepts of flexibility and antifragility into supply chain frameworks. Resilience, defined as a system's capacity to address external and internal changes to maintain or enhance competitive advantage, is critical for responsiveness [3], [4].

The construction industry has emerged as a vital strategic instrument in Iran's industrialization efforts over the past decade [5]. However, many companies have shown reluctance to adopt and implement novel concepts. Similarly, despite awareness of the construction sector's significant impact on developing economies like Iran, researchers and experts have devoted insufficient attention to this field.

The complexity arising from regional interactions and risks stemming from economic-political instability underscores the necessity for supply chain resilience. In such contexts, managerial focus extends beyond mere efficiency; strategic decisions across the supply chain must enable rapid responses to disruptions, facilitate recovery, and enhance performance to levels surpassing pre-disruption states [6]. Given that risks are uncontrollable, and disruptions and uncertainties are diverse and unpredictable, supply chain vulnerabilities are perpetually targeted. Thus, adopting a resilience-oriented approach is imperative.

In the era of the Fourth Industrial Revolution (Industry 4.0), businesses must not only react to risks but also anticipate and plan strategically, adopting a comprehensive and agile perspective to adapt operations dynamically. Stakeholders are increasingly urged to enhance awareness and understanding of resilience and antifragility concepts, implementing practices that positively impact the value chain within the Industry 4.0 framework [7]. The operations of construction firms, embedded in multilayered and complex supply chains, highlight the critical role of resilience in the Industry 4.0 context. The integration of digital technologies into supply chains has rendered them more agile, responsive, and transparent, enabling greater adaptability to changing conditions and mitigating the impact of disruptions [4].

Rapid advancements in Industry 4.0 technologies have transformed business architectures. The uncertainties associated with adopting Industry 4.0 and the inherent weaknesses of conventional supply chains elevate the importance of resilience. These factors necessitate a simultaneous examination of resilience and Industry 4.0 within one of Iran's most strategic supply chains in its developing economy. The hallmarks of the modern industrial revolution—strategic thinking and strategic change—are among the most prominent managerial tools for optimally addressing evolving business environments [7], [8].

Industry 4.0 innovations and associated strategic concepts play a pivotal role in enhancing the scalability and flexibility of supply chain processes, enabling cost-effective and timely responses to and recovery from unforeseen events [9]. Characterized by transformative technologies such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), Big Data (BD), additive manufacturing, Cloud Computing (CC), blockchain, drones, sensors, 3D printing, robotics, and Artificial Intelligence (AI), Industry 4.0 has profoundly influenced production processes and mental models, consequently reshaping supply chain management. Although many industries across diverse economies have adopted these technologies, a lack of deep managerial understanding of the underlying scientific concepts has hindered the realization of their full potential.

The essence of Industry 4.0 has transformed it into a paradigm shift within the industrial landscape. Consequently, the concept of competitive advantage has undergone a profound evolution, challenging traditional notions of sustainability and replicability in the architecture of modern business strategies.

Given the multifaceted nature of supply chains, the significant number of stakeholders, and the complexity and diversity of Industry 4.0 concepts, further research is essential to address knowledge gaps and align with advancements in scientific and industrial domains. Industry 4.0 technologies and concepts significantly enhance flexibility, agility, robustness, transparency, and information sharing, all of which bolster supply chain resilience [10–14]. Nonetheless, empirical research exploring the interplay between resilience, strategic supply chain management, and the construction industry within the Industry 4.0 paradigm remains limited.

The literature is replete with studies demonstrating the impact of individual disruptive technologies and Industry 4.0 concepts on supply chain performance. However, there is a critical need for integrated research to synthesize these findings. Data collected from Industry 4.0 technologies, when processed, can provide valuable insights, reveal interdependencies, and illuminate dynamic and static relationships, significantly aiding managerial decision-making [15]. The underlying rationale of this research is to prioritize factors influencing the enablers of strategic management in resilient supply chains, with a focus on Industry 4.0 within Iran's construction industry, fostering a more connected and efficient industrial ecosystem.

While Industry 5.0 has been introduced and adopted in developed economies, developing economies like Iran are still transitioning toward full Industry 4.0 adoption. Although AI is a common thread between both industrial paradigms, the nature of human-machine interactions differs significantly [16]. Advanced industrial nations have progressed beyond Industry 4.0 to embrace Industry 5.0, while developing economies, recently adopting Industry 4.0, face associated challenges. Whether implementing Industry 4.0 or transitioning to Industry 5.0, leveraging modern, AI-driven disruptive technologies is a critical tool for strategic management aimed at mitigating supply chain disruptions, with profound implications for resilience [16]. Post-COVID research clearly indicates that achieving supply chain resilience is unattainable without integrating foundational Industry 4.0 or Industry 5.0 concepts and disruptive technologies.

The evaluation of heterogeneous, inconsistent, and unreliable information amidst the multifaceted challenges of the industrial landscape is a frequently addressed topic in decision-making literature. Despite the plethora of available methods, selecting an approach that maximizes value remains a subject of ongoing debate and scrutiny.

Strategic management of resilient supply chains within the Industry 4.0 paradigm necessitates precise and tailored decision-making methodologies due to its reliance on the knowledge, experience, and expertise of domain experts. Extracting insights from expert opinions and transforming them into actionable knowledge requires robust decision-making frameworks capable of navigating uncertainty. Consequently, the application of fuzzy set theory, which has demonstrated reliable outcomes across diverse studies, becomes indispensable [17–19]. Among the various fuzzy set frameworks introduced, this study employs the basic fuzzy set due to its simplicity and precision, rendering it the most widely adopted variant.

The Fuzzy Evaluation based on Distance from Average Solution (Fuzzy EDAS) model [20], [21] accounts for information uncertainty while offering a coherent, logical, and objective decision-making capability, making it a suitable tool for this research. Introduced in 2015, the Fuzzy EDAS method [22] has rapidly gained traction and been extended across various research domains [23]. Shortly after its inception, researchers began integrating EDAS with other decision-making techniques and theories, such as fuzzy and grey systems, to address managerial hesitancy in decision-making processes [24]. The systematic integration of EDAS with fuzzy theory effectively incorporates uncertainties inherent in managerial decision-making.

Among Multi-Criteria Decision-Making (MCDM) techniques, certain methods base their evaluations on distance or similarity to a specific solution. This approach has given rise to methods such as TOPSIS, VIKOR, and EDAS. The former two prioritize similarity to an ideal solution, while EDAS focuses on the distance from an average solution. Specifically, in TOPSIS, the optimal solution minimizes the distance to the positive ideal solution while maximizing the distance to the negative ideal solution. In VIKOR, the best and worst solutions are identified for each alternative to determine a compromise solution. Conversely, EDAS evaluates alternatives based on their positive and negative distances from the average solution [25].

Established research has extensively explored supply chain resilience. However, this study seeks to address an overlooked perspective by examining resilience within the context of Industry 4.0 and the construction sector. To this end, it integrates existing knowledge with novel findings derived from this research. Flexibility is critical for managing disruptions of varying origins within the supply chain. This study aims to propose strategies that equip managers with tools to respond effectively to disruptions and, when necessary, pivot operations. Preparedness for emergencies, a cornerstone of resilience, can facilitate the development of robust emergency response protocols. Supply chains in the construction industry must exhibit flexibility, which necessitates strategic management frameworks aligned with Industry 4.0 tools.

The remainder of the manuscript is organized as follows: Section 2 provides a review of the literature on the subject. A description of the methodology used is presented in Section 3. Section 4 describes the results of the model implementation step by step. Finally, in Section 5, the results and findings obtained are discussed.

2 | Literature Review

This section provides a concise and transparent overview of the key concepts addressed in this study.

2.1 | Resilient Supply Chain

The concept of the supply chain, defined as the management of all processes and activities that create value for the end customer, was introduced in 1985. Subsequent scholarly efforts have conceptualized it from various perspectives, such as cost-effectiveness, time efficiency, and other dimensions, asserting that appropriate products must be delivered in the right quantities, at the right time and place, and at an acceptable price and quality level [26]. A widely accepted contemporary definition describes the supply chain as a network of processes and organizations—including suppliers, customers, production sites, distributors, and retailers—involved in fulfilling customer orders, encompassing core operations such as planning, sourcing, manufacturing, delivery, and returns [7].

The primary objective of a supply chain is to reduce costs, enhance effectiveness and efficiency, and ultimately increase profitability for all stakeholders across all levels. However, ensuring reliable products and services through efficient and effective management of information and material flows is no longer sufficient. Dynamic and robust supply chains require flexibility and resilience [6]. Resilient supply chains are an interdisciplinary concept, drawing from psychology, engineering, ecology, and economics [27]. Resilience is defined across disruption and risk phases—pre-disruption, during disruption, and post-disruption [27]. Assuming an engineered supply chain behaviour, resilience enables a return to a stable state akin to pre-disruption conditions or even a leap to an improved state [28]. Engineering resilience emphasizes stabilization to a balanced state, enhancing resistance to disruptions and accelerating recovery. An alternative socio-ecological interpretation focuses not on maintaining an ostensibly optimal supply chain state but on reorganization, development, and a willingness to experiment, embracing change to preserve core functions. This perspective highlights non-linear dynamics and uncertainty [29]. Ecological resilience is defined by the magnitude of disruption a system can absorb before shifting to a new behavioural state, emphasizing adaptability, transformation, and unpredictability. Managers adopting this view acknowledge that disruptions can fundamentally alter a system's behaviour.

Resilient supply chains encompass three dimensions: absorption and adaptability [30], responsiveness and preparedness [31], and recovery. The first dimension reflects situational awareness, redundancy, and visibility within the supply chain (Ivanov,2022). The second serves as a defensive mechanism against disruptions [32]. Recovery encompasses efficiency, contingency planning, and knowledge management. By integrating knowledge about disruption events and leveraging feedback, firms can develop superior solutions for future supply chain operations, achieving enhanced performance [28].

Companies implementing resilient supply chain management encounter challenges, the analysis of which can contribute to the existing body of knowledge [9]. Some studies have employed fuzzy decision-making frameworks to rank these barriers in uncertain environments [13]. Building flexibility within a value chain requires identifying disruptions and risks and implementing strategic management practices to address them [11].

2.2 | Construction Industry Supply Chain

The construction industry is undergoing a profound transformation driven by the disruptions and conditions of the past decade. These circumstances have created significant potential for fundamental changes in the management of the industry's supply chain. Construction firms were identified as particularly vulnerable during the COVID-19 pandemic [33], experiencing various disruptions, including a reduction in the number of suppliers. To ensure business continuity, the industry has adopted concepts such as green supply chains [5], the integration of advanced technologies like blockchain within the supply chain [34], and the application of circular economy principles as a strategic solution (Source R3). Additionally, resilient and agile strategies have been employed to maintain and enhance competitive advantages within the construction supply chain [3].

The core of implementing modern construction techniques lies within the industry's supply chain [3]. This stems from the fact that the construction supply chain is considerably more complex and extensive compared to many other industries. The adoption and development of new technologies in this supply chain have advanced to include applications such as Digital Twins in architecture, engineering, construction, and operations [12]. However, only a limited number of studies have explored this topic. Digital Twins require advanced technical expertise in AI and a high level of technological maturity, which is currently more accessible to developed nations. Given the benefits of Digital Twins in addressing the complexities of the construction industry, serious attention to the requirements for their implementation is warranted.

Research on risk management within the construction industry has also been conducted [35]. The concept of sustainability has been extensively explored in a wide array of studies, focusing on the management of materials, information, and capital while addressing environmental, social, and economic considerations [36]. Furthermore, investigations targeting the reduction of carbon emissions and greenhouse gases in the construction industry have been undertaken [37], [38].

2.3 | Industry 4.0 and Supply Chain Management

The Fourth Industrial Revolution, closely associated with the German government's initiative [39], initially focused on integrating digital technologies into industrial factories to enable smart manufacturing and enhance productivity [40]. Industry 4.0 transcends mere technological advancements, serving as a catalyst for the emergence of novel concepts in production and extending to supply chain management. Subsequently, it became customary to explore concepts such as sustainability, circular economy, lean culture, and cleaner production within the Industry 4.0 framework [8], [39], [41]. Implementing these concepts in supply chains necessitated mechanisms and digital platforms that foster transparency and resilience [11].

The adoption of digital technologies—such as blockchain, intelligent robotics, drones, and AI—across various supply chains, particularly in the construction industry, has fundamentally transformed management practices, becoming a critical imperative [42]. These technologies have significantly reduced information silos across supply chain tiers, enabling seamless connectivity among diverse chain levels and types [43], [44]. This interconnected and intelligent environment propels supply chains toward digital transformation (additional source required). The transformative and multifaceted impact of these technologies on environmental, ethical, and sustainability outcomes paves the way for a pioneering and responsive construction ecosystem, while simultaneously enhancing stakeholder trust [45].

In 2021, Deloitte reported that 69% of construction firms prioritize adopting these technologies, reflecting their eagerness to embrace revolutionary changes [46]. The high potential of these technologies, applicable across various supply chain dimensions, heralds a new era of innovation and collaboration. However, this transition introduces challenges, including digital literacy, process redefinition, skilled human capital, agile leadership, financial resources, and regulatory frameworks [4]. Collectively, these factors position construction supply chain management at the precipice of a new era.

Blockchain technology facilitates transparent, real-time information exchange among parties, optimizes operational processes, and reduces reliance on physical documentation throughout the supply chain [47], [34]. Additionally, blockchain enhances energy management within supply chains, contributing to resilience [15]. Traditional supply chains, by simultaneously adopting blockchain and the Industrial Internet of Things (IIoT), are rapidly evolving toward industrial ecosystems aligned with Industry 4.0 frameworks [24]. Intelligent robotic systems, coupled with digital technologies, data analytics, and data-driven decision-making, have introduced a new paradigm for maintenance and repair in supply chains, resulting in cost reductions and enhanced efficiency [24].

The knowledge underpinning Industry 4.0 technologies can rapidly disseminate and be readily replicated by agile competitors. Coupled with the exponential pace of technological advancements and the industry's openness to adopting them, firms no longer adhere to traditional perspectives on sustainable competitive advantage in this revolution. Despite the ephemeral nature of advantages in this transformation, companies are compelled to repeatedly generate continuous innovation aligned with technological progress as a new form of competitive edge. This cycle of innovation, imitation, and renewal defines the modern competitive landscape. With the advent of Industry 4.0 and Industry 5.0, traditional efforts to achieve sustainable competitive advantage have been supplanted by the relentless pursuit of opportunities. According to McKinsey and Company and Deloitte, the victors in this era are those who can deliver "better, faster," not merely once, but repeatedly.

Implementing technologies such as AI and the IoT in the digital transformation journey of construction supply chains requires collaboration among all stakeholders, standardization, updated protocols, and solutions to scalability challenges. The application of Industry 4.0 technologies and concepts—from intelligent robotics to BD and CC—has a proven role in optimizing logistics, improving supply chain efficiency, and reducing costs [10]. Industry 4.0 technologies empower managers with robust tools to confidently navigate the evolving industrial landscape. Consequently, they recognize that the survival of resilient supply chains hinges on adopting AI-driven requirements [16]. Industry 4.0 has spurred diverse innovations, each tailored to its application domain, elevating business models accordingly [48].

2.4 | Extracting Research Criteria

Based on the concepts discussed thus far, a questionnaire was developed incorporating the following criteria and sub-criteria. This study aims to identify and prioritize the factors influencing the enablement of strategic management in resilient supply chains within the context of Industry 4.0, specifically in Iran's construction industry. Three primary criteria were established: Human Capital (C1–C4), Technological Development in the Supply Chain (C5–C9), and Supply Chain Capabilities (C10–C14).

Human capital (C1–C4): The first criterion, Human Capital, is subdivided into four sub-criteria: Managerial Capabilities (C1) [49], Employee Experience and Skills (C2) [49], Transformational Leadership (C3) [49], and Creative and Innovative Employees (C4) [50]. The adoption of Industry 4.0 presents significant challenges for organizations, with one of the most critical being the need for a workforce equipped with the skills and knowledge to leverage advanced technologies. While automation poses risks of job displacement, investments in training programs and other initiatives can enable employees to acquire or update the skills necessary for their roles. The role of leaders in such organizations is pivotal [41]. These leaders must foster intellectual stimulation, motivation, commitment, and effort within themselves and their teams to prepare for the challenges of this industrial revolution. Traditional mindsets are inadequate for navigating the new era of Industry 4.0; leaders and employees must reorganize or elevate their values and behaviors, achieving a level of self-transcendence. They must identify needs, create aligned individual and team visions, drive necessary changes, and take ownership of their work. Employees must enhance their digital literacy and adapt their skills to align with the technologies in use. In the volatile and uncertain context of developing economies, organizations require strategic decision-making by leaders who possess the art and science of leadership in the modern industrial era.

Technological development in the supply chain (C5–C9): The second criterion encompasses the sub-criteria; IoT (C5) [27], Blockchain (C6), CC (C7), AI (C8) [51], and digitization of supervisory production processes (C9) [27]. These technologies are critical enablers of Industry 4.0, driving efficiency and innovation in supply chain operations.

Supply chain capabilities (C10–C14): The third criterion includes the sub-criteria: integration and collaboration among supply chain members (C10), Proactive Preparedness Through Forecasting (C11), reactive responsiveness through agility (C12), innovative organizational culture (C13) [27], and supply chain system dynamics (C14). These capabilities are essential for building resilient and adaptive supply chains.

It is reiterated that the adoption of Industry 4.0 technologies requires the establishment of an enabling infrastructure, which enhances the speed and efficiency of process execution. Given resource constraints, prioritizing the implementation of these sub-criteria is imperative to ensure effective integration and maximize impact.

3 | Methodology

3.1 | Delphi Technique

The Delphi technique, aptly named after the oracle of Delphi—a revered site for prophecies and counsel in ancient Greece—is a structured method designed to aggregate the opinions and insights of experts on a specific topic. This approach facilitates the collection of diverse expert perspectives while minimizing social biases and group pressures through participant anonymity. Although not without limitations, the Delphi method is employed in this study to achieve an initial consensus on the validity of the identified sub-criteria. In the first stage, expert forecasts are collected, anonymized, and aggregated by calculating the mean of the responses. Subsequently, refined questions are redistributed to the experts. In the second stage, experts are invited to reassess their estimates, and the process is reiterated. During this iterative procedure, experts may adjust or refine their forecasts, while those confident in their initial predictions may opt to retain them. This cycle continues until a satisfactory average estimate is achieved. The success of this method hinges on the development of a clear and well-constructed questionnaire grounded in a precise understanding of the research problem.

3.2 | Fuzzy EDAS Method

The Fuzzy EDAS method is founded on assessing alternatives by measuring their distance from the average solution. This approach accounts for uncertainty in decision-making, leveraging fuzzy logic to provide a coherent, logical, and objective evaluation framework, making it particularly suitable for prioritizing factors in complex and uncertain environments like resilient supply chain management. The fuzzy EDAS technique, introduced by Keshavarz Ghorabaee et al. [52], is utilized in this study to evaluate expert opinions expressed as linguistic terms for each criterion. These linguistic terms are assessed using positive triangular fuzzy numbers. The steps of the Fuzzy EDAS method are outlined below [22]:

Step 1 (Formation of the decision matrix). The decision matrix is constructed based on the evaluation of criteria by each expert, where criteria are denoted by *i* and experts by j. The matrix is formed using *Eq. (1)*,

$$X = \left[\tilde{X}_{ij}\right]_{n\times m}. \tag{1}$$

where, $\tilde{X}_{ij}$ represents the score of criterion i by expert j. The linguistic scale from *Table 1* is used to populate the decision matrix.

Table 1. Linguistic terms and corresponding fuzzy numbers for ranking options [53].

Code	Priority	Fuzzy Equivalent (L, M, U)
1	Very low	(1, 1, 3)
2	Low	(1, 3, 5)
3	Medium	(3, 5, 7)
4	High	(5, 7, 9)
5	Very high	(7, 9, 11)

Step 2 (Determination of average scores for each expert). The arithmetic mean of each expert's scores for each criterion is calculated using *Eq. (2)* and *Eq. (3),* where, $\widetilde{av}_j$ represents the average of the scores in each column of the decision matrix.

$$AV = \left[\widetilde{av}_j\right]_{1\times m}. \quad (2)$$

$$\widetilde{av}_j = \frac{1}{k}\sum_{i=1}^{n} \tilde{X}_{ij}. \quad (3)$$

Step 3 (Determination of positive and negative distances from the average). The positive distance from the average (Pda) and Negative Distance From the Average (Nda) matrices are computed based on the type of criterion, as shown in *Eq. (4)* and *Eq. (5).* In these equations, $k(\widetilde{av}_j)$ is the defuzzified average of each column, and $\tilde{x}_{ij} \ominus \widetilde{av}_j$ represents the difference between each score in the decision matrix and the column average.

$$P\tilde{d}a_{ij} = \frac{\psi\left(\tilde{x}_{ij} \ominus \widetilde{av}_j\right)}{k\left(\widetilde{av}_j\right)}. \quad (4)$$

$$n\tilde{d}a_{ij} = \frac{\psi\left(\widetilde{av}_j \ominus \tilde{x}_{ij}\right)}{k\left(\widetilde{av}_j\right)}. \quad (5)$$

$$\psi = \begin{cases} 1, & X > 0, \\ 0, & X \leqslant 0. \end{cases}$$

The symbol ψ indicates a binary condition: if the value inside the parentheses is greater than zero, it equals 1; otherwise, it equals 0.

Step 4 (Calculation of weighted sum of positive and negative distances). The weighted sums of positive distances $\widetilde{sp}_i$ and negative distances $\widetilde{sn}_i$ for all criteria are calculated using *Eq. (6)* and *Eq. (7),* where W_j denotes the weight of expert j.

$$\widetilde{sp}_i = \sum_{j=1}^{m}\left(W_j \otimes P\tilde{d}a_{ij}\right). \quad (6)$$

$$\widetilde{sn}_i = \sum_{j=1}^{m}\left(W_j \otimes n\tilde{d}a_{ij}\right). \quad (7)$$

Step 5 (Normalization of (SP) and (SN)). The normalized values of $\widetilde{sp}_i$ and $\widetilde{sn}_i$ for all criteria are computed using *Eq. (8)* and *Eq. (9)*, where $k(\widetilde{sp})_i$ are the defuzzified values of the positive and negative distances.

$$n\widetilde{sp}_i = \frac{\widetilde{sp}_i}{\max_i\left(k(\widetilde{sp})_i\right)}. \quad (8)$$

$$n\widetilde{sn}_i = 1 - \frac{\widetilde{sn}_i}{\max_i\left(k(\widetilde{sn})_i\right)}. \quad (9)$$

Step 6 (Determination of final scores and ranking of criteria). The final appraisal score $\tilde{as}_i$ for each criterion is calculated using *Eq. (10).* Criteria are ranked based on their appraisal scores, with higher scores indicating superior criteria.

$$\tilde{as}_i = \frac{1}{2}\left(n\tilde{s}p_i + n\tilde{s}n_i\right). \quad (10)$$

4 | Results

4.1 | Results of the Delphi Technique

The statistical population of this study comprises twenty experts and contractors associated with the construction industry, each possessing a minimum of five years of professional experience and holding at least a master's degree in civil engineering or architecture. Academic experts confirmed the validity of the designed questionnaire, and its reliability was calculated to be 0.884 using the SPSS statistical software.

As previously noted, the factors influencing the enablement of strategic management in resilient supply chains were identified through a literature review. A questionnaire was then distributed to experts, who rated each indicator on a five-point Likert scale (1= Very Low Importance, 2= Low Importance, 3= Medium Importance, 4= High Importance, 5= Very High Importance). The mean score for each indicator was calculated, and indicators with a mean score below 3 were excluded, while those above 3 were retained. The results are presented in *Table 2*.

Table 2. Results of factor evaluation.

Criterion	Sub-Criterion	Mean Score
Human capital	Managerial capabilities	4.1
	Employee experience and skills	4.05
	Transformational leadership	3.9
	Creative and innovative employees	3.4
Technological development	Internet of things	3.4
	Blockchain	3.45
	Cloud computing	3.75
	Artificial intelligence	3.75
	Digitization of production and supervisory processes	3.75
Supply chain capabilities	Integration and collaboration	3.45
	Proactive preparedness through forecasting	3.25
	Reactive responsiveness through agility	3.2
	Innovative organizational culture	3.45
	Supply chain system dynamics	3.65

All indicators achieved a mean score above 3, confirming their validity for inclusion in the study.

4.2 | Results of the Delphi Technique

This section presents the ranking of the 14 validated criteria using the Fuzzy EDAS method.

Step 1 (Formation of the decision matrix). The decision matrix is constructed based on *Eq. (1)*, comprising 14 criteria evaluated by 20 experts. The matrix is populated using the linguistic scale from *Table 1*. The resulting decision matrix is shown in *Table 3*.

Table 3. Fuzzy EDAS decision matrix.

	Expert 1	Expert 2	…	Expert 19	Expert 20
C1	(3,5,7)	(5,7,9)	…	(5,7,9)	(7,9,11)
C2	(5,7,9)	(7,9,11)	…	(5,7,9)	(7,9,11)
C3	(5,7,9)	(7,9,11)	…	(1,3,5)	(7,9,11)
C4	(5,7,9)	(5,7,9)	…	(5,7,9)	(5,7,9)
C5	(3,5,7)	(5,7,9)	…	(5,7,9)	(1,1,3)
C6	(3,5,7)	(5,7,9)	…	(1,3,5)	(7,9,11)
C7	(7,9,11)	(5,7,9)	…	(5,7,9)	(7,9,11)
C8	(5,7,9)	(5,7,9)	…	(5,7,9)	(7,9,11)
C9	(1,3,5)	(7,9,11)	…	(5,7,9)	(7,9,11)
C10	(1,3,5)	(5,7,9)	…	(5,7,9)	(7,9,11)
C11	(1,3,5)	(5,7,9)	…	(1,3,5)	(7,9,11)
C12	(3,5,7)	(3,5,7)	…	(1,3,5)	(7,9,11)
C13	(1,3,5)	(5,7,9)	…	(5,7,9)	(7,9,11)
C14	(5,7,9)	(5,7,9)	…	(5,7,9)	(7,9,11)

Step 2 (Determination of average scores for each expert). The arithmetic mean of each expert's scores is calculated using *Eq. (2)* and *Eq. (3)*. The results are presented in *Table 4*.

Table 4. Average scores for each criterion.

	Expert 1	Expert 2	…	Expert 19	Expert 20
Mean	(3.429,5.429,7.429)	(5.286,7.286,9.286)	…	(3.857,5.857,7.857)	(6.429,8.286,10.286)

Step 3 (Determination of positive and negative distances from the average). Using *Eq. (4)* and *Eq. (5)*, the positive and negative distances from the average are calculated. The results are shown in *Tables 5* and *6*.

Table 5. Positive Distance from Average (PDA).

	Expert 1	Expert 2	…	Expert 19	Expert 20
C1	(0,0,0)	(0,0,0)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)
C2	(-0.447,0.289,1.026)	(-0.314,0.235,0.784)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)
C3	(-0.447,0.289,1.026)	(-0.314,0.235,0.784)	…	(0,0,0)	(-0.395,0.086,0.549)
C4	(-0.447,0.289,1.026)	(0,0,0)	…	(-0.488,0.195,0.878)	(0,0,0)
C5	(0,0,0)	(0,0,0)	…	(-0.488,0.195,0.878)	(0,0,0)
C6	(0,0,0)	(0,0,0)	…	(0,0,0)	(-0.395,0.086,0.549)
C7	(-0.079,0.658,1.395)	(0,0,0)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)
C8	(-0.447,0.289,1.026)	(0,0,0)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)
C9	(0,0,0)	(-0.314,0.235,0.784)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)
C10	(0,0,0)	(0,0,0)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)
C11	(0,0,0)	(0,0,0)	…	(0,0,0)	(-0.395,0.086,0.549)
C12	(0,0,0)	(0,0,0)	…	(0,0,0)	(-0.395,0.086,0.549)
C13	(0,0,0)	(0,0,0)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)
C14	(-0.447,0.289,1.026)	(0,0,0)	…	(-0.488,0.195,0.878)	(-0.395,0.086,0.549)

Table 6. Negative Distance from Average (NDA).

Expert 1	Expert 2	…	Expert 19	Expert 20
(-0.658,0.079,0.816)	(-0.51,0.039,0.588)	…	(0,0,0)	(0,0,0)
(0,0,0)	(0,0,0)	…	(0,0,0)	(0,0,0)
(0,0,0)	(0,0,0)	…	(-0.195,0.488,1.171)	(0,0,0)
(0,0,0)	(-0.51,0.039,0.588)	…	(0,0,0)	(-0.309,0.155,0.635)
(-0.658,0.079,0.816)	(-0.51,0.039,0.588)	…	(0,0,0)	(0.412,0.876,1.116)
(-0.658,0.079,0.816)	(-0.51,0.039,0.588)	…	(-0.195,0.488,1.171)	(0,0,0)
(0,0,0)	(-0.51,0.039,0.588)	…	(0,0,0)	(0,0,0)
(0,0,0)	(-0.51,0.039,0.588)	…	(0,0,0)	(0,0,0)
(-0.289,0.447,1.184)	(0,0,0)	…	(0,0,0)	(0,0,0)
(-0.289,0.447,1.184)	(-0.51,0.039,0.588)	…	(0,0,0)	(0,0,0)
(-0.289,0.447,1.184)	(-0.51,0.039,0.588)	…	(-0.195,0.488,1.171)	(0,0,0)
(-0.658,0.079,0.816)	(-0.235,0.314,0.863)	…	(-0.195,0.488,1.171)	(0,0,0)
(-0.289,0.447,1.184)	(-0.51,0.039,0.588)	…	(0,0,0)	(0,0,0)
(0,0,0)	(-0.51,0.039,0.588)	…	(0,0,0)	(0,0,0)

Step 4 (Calculation of weighted sum of positive and negative distances). Using *Eq. (6)* and *Eq. (7)*, the weighted sums of positive and negative distances are computed by multiplying the expert weights (set at 0.05 for 20 experts) by the values in *Table 5* and *Table 6* and summing them row-wise. The results are shown in *Table 7*.

Table 7. Weighted sums of positive and negative distances ((SP) and (SN)).

	(SP)	(SN)
C1	(-0.339,0.199,0.723)	(-0.107,0.017,0.141)
C2	(-0.334,0.205,0.737)	(-0.06,0.057,0.179)
C3	(-0.286,0.16,0.599)	(-0.152,0.058,0.274)
C4	(-0.195,0.058,0.309)	(-0.254,0.143,0.552)
C5	(-0.243,0.072,0.376)	(-0.168,0.176,0.511)
C6	(-0.305,0.072,0.445)	(-0.145,0.13,0.395)
C7	(-0.266,0.179,0.612)	(-0.106,0.11,0.313)
C8	(-0.279,0.132,0.54)	(-0.151,0.089,0.34)
C9	(-0.294,0.131,0.554)	(-0.114,0.112,0.303)
C10	(-0.271,0.097,0.456)	(-0.143,0.146,0.42)
C11	(-0.178,0.075,0.321)	(-0.208,0.194,0.577)
C12	(-0.181,0.066,0.307)	(-0.204,0.204,0.593)
C13	(-0.304,0.099,0.489)	(-0.126,0.132,0.375)
C14	(-0.242,0.155,0.545)	(-0.13,0.129,0.394)

Step 5 (Normalization of (SP) and (SN)). The normalized values of (SP) and (SN) are calculated using *Eq. (8)* and *Eq. (9)*. The results are presented in *Table 8*.

Table 8. Normalized Values of (SP) and (SN).

	(NSP)	(NSN)
C1	(-1.666,0.978,3.558)	(0.29,0.914,1.537)
C2	(-1.644,1.009,3.626)	(0.101,0.715,1.302)
C3	(-1.405,0.789,2.946)	(-0.375,0.707,1.762)
C4	(-0.962,0.283,1.523)	(-1.767,0.283,2.274)
C5	(-1.195,0.355,1.851)	(-1.564,0.115,1.844)
C6	(-1.5,0.353,2.191)	(-0.984,0.345,1.726)
C7	(-1.308,0.881,3.01)	(-0.57,0.446,1.53)
C8	(-1.373,0.65,2.657)	(-0.706,0.552,1.76)
C9	(-1.445,0.645,2.726)	(-0.519,0.438,1.571)
C10	(-1.333,0.476,2.243)	(-1.107,0.266,1.72)
C11	(-0.877,0.367,1.581)	(-1.893,0.027,2.044)
C12	(-0.89,0.326,1.512)	(-1.973,-0.024,2.021)
C13	(-1.494,0.485,2.405)	(-0.879,0.336,1.632)
C14	(-1.19,0.764,2.682)	(-0.975,0.353,1.652)

Step 6 (Determination of final scores and ranking of criteria). The final fuzzy appraisal scores are calculated using *Eq. (10)*, and the results are shown in *Table 9*. Managerial Capabilities (C1) achieved the highest rank, followed by Employee Experience and Skills (C2) in second place, and Transformational Leadership (C3) in third. The rankings of the remaining criteria are shown in *Table 9*.

Table 9. Final scores and ranking of criteria.

Criterion	Code	Fuzzy Score	Defuzzified Score	Rank
Managerial capabilities	C1	(-0.688,0.946,2.548)	0.9379	1
Employee experience and skills	C2	(-0.772,0.862,2.464)	0.8542	2
Transformational leadership	C3	(-0.89,0.748,2.354)	0.7400	3
Cloud computing	C7	(-0.939,0.663,2.27)	0.6644	4
Artificial intelligence	C8	(-1.039,0.601,2.208)	0.5926	5
Digitization of production and supervisory processes	C9	(-0.982,0.541,2.148)	0.5623	6
Supply chain system dynamics	C14	(-1.082,0.559,2.167)	0.5504	7
Innovative organizational culture	C13	(-1.187,0.41,2.019)	0.4132	8
Integration and collaboration	C10	(-1.22,0.371,1.981)	0.3760	9
Blockchain	C6	(-1.242,0.349,1.959)	0.3538	10
Creative and innovative employees	C4	(-1.365,0.283,1.898)	0.2750	11
Internet of things	C5	(-1.379,0.235,1.848)	0.2347	12
Proactive preparedness through forecasting	C11	(-1.385,0.197,1.812)	0.2053	13
Reactive responsiveness through agility	C12	(-1.432,0.151,1.767)	0.1592	14

5 | Discussion and Conclusion

Through a comprehensive review of documented insights, the factors influencing the research topic were identified. Given the inherent uncertainties in Iran's economic landscape, the Fuzzy EDAS method was employed to prioritize these factors. This approach addresses a significant research gap concerning the transition to Industry 4.0 while simultaneously considering supply chain resilience in the construction industry within a developing economy. The study reveals that, while Industry 4.0 concepts and technologies are essential for enhancing the performance of multilayered construction supply chains with diverse and sometimes conflicting roles, Managerial Capabilities, Employee Experience and Skills, and Transformational Leadership remain highly prioritized by experts for navigating the transition to modern industrial conditions.

The findings highlight a compelling paradox: despite the prominent role of emerging technologies in rearchitecting business models and creating value, human resources and their attributes—across all organizational levels, including managers and employees—play a decisive role in elevating strategic organizational success. In other words, the art and science of leadership, combined with the soft and hard skills of managers and employees, can steer Industry 4.0 concepts and technologies to manage uncertainties in resilient supply chains and generate value.

Rapid innovation, as a key driver, is regarded as a source of transient competitive advantage. Consequently, organizations must cultivate adaptive structures and cultures that support continuous experimentation and learning. By consistently investing in workforce skill development, digital infrastructure, and innovative processes, firms can repeatedly create new, albeit temporary, advantages. As this research is grounded in extracting subjective expert knowledge, the use of uncertainty theories is unavoidable. Therefore, it is recommended that future studies employ other fuzzy set models and decision-making frameworks [54] and compare their results with those of this study.

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