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Prioritization of Supply Chain Digital Transformation Strategies Using Multi-Expert Fermatean Fuzzy Analytic Hierarchy Process

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Abstract. Innovations in technology emerged with digitalization affect all sectors, including supply chain and logistics. The term "digital supply chain" has arisen as a relatively new concept in the manufacturing and service sectors. Organizations planning to utilize the benefits of digitalization, especially in the supply chain area, have uncertainties on how to adapt digitalization, which criteria they will evaluate, what kind of strategies should be developed, and which should be given more importance. Multi-criteria decision making (MCDM) approaches can be addressed to determine the best strategy under various criteria in digital transformation. Because of the need to capture this uncertainty, fermatean fuzzy sets (FFSs) have been preferred in the study to widen the definition domain of uncertainty parameters. Interval-valued fermatean fuzzy sets (IVFFSs) are one of the most often used fuzzy set extensions to cope with uncertainty. Therefore, a new interval-valued fermatean fuzzy analytic hierarchy process (IVFF-AHP) method has been developed. After determining the main criteria and sub-criteria, the IVFF-AHP method has been used for calculating the criteria weights and ranking the alternatives. By determining the most important strategy and criteria, the study provides a comprehensive framework of digital transformation in the supply chain.

Key words: digital transformation, supply chain, fermatean fuzzy sets, MCDM, AHP.

1. Introduction

Technological advances with Industry 4.0 have enabled consumers to buy whatever they want, wherever they want, whenever they want. This has necessitated the supply chains to be digital, intelligent, and integrated. Thus, "digital supply chain" or "supply chain 4.0" introduced in the industrial world has been one of the fastest rising trends in both academy and industry. While the organizational structure in traditional supply chains is often defined by functional and geographic silos that do not share information, digital supply chains have broad information asset capability, as well as provide superior collaboration and communication between digital platforms resulting in enhanced agility, efficiency and reliability (Raab and Griffin-Cryan, 2011). Digital Supply Chain (DSC)

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has a customer-centric model, using real-time data from various sources. DSC optimizes performance and minimizes risk through demand matching, stimulation, sensing and management (The Center for Global Enterprise, 2015). But many global supply chains are unequipped to cope with the world we are entering. Therefore, supply chain managers need to alter their attention enabling new processes and cutting costs and should make institutes more connected and agile to create value across the institution (Farahani *et al.*, 2020). With technological advances, emerging new digital technologies have deeply altered the way people communicate and interact with their enclosing. Technological novelties and personal gadgets, such as 3D printing, internet of things, big data, cloud, augmented reality, personal computers, smartphones, self-driving cars, mobile devices, advanced television units, drones, smartwatches, and wearable devices change the way societies access and exchange information (Büyüközkan and Göçer, 2018a). These technologies will provide the digitalization of products and services and new business models (PwC Sweden, 2018). Although many organizations have initiated a digital transformation in supply chains, they have not tackled a holistic approach to their DSC and it have been caused this situation to be in initial development stages until now. Hence, the biggest obstacle to successful digital transformation in the supply chain is the lack of digital strategies in organizations (PwC Sweden, 2018). Digital strategy implementation focuses on the entire supply chain, addressing the questions of "how, where, when and by whom" goals and objectives will be achieved (Büyüközkan and Göçer, 2018a). Organizations need to evaluate their strategies according to certain criteria in order to obtain a successful digital transformation in the supply chain and to create a roadmap. But, there is a lack of a strategic road map to guide organizations in the literature. Therefore, there has been a need for a comprehensive strategic roadmap carefully identifying and planning the digital transformation of organizations. Besides, it is known that in the literature there is no evaluation of digital transformation strategies in the supply chain with a MCDM approach. For this emerging need, organizations should be evaluated by considering together more than one criteria and so, they must use a MCDM method. MCDM includes several main and sub criteria, which can be tangible or intangible and used to rank the alternatives during a decision process. There are numerous MCDM methods in the literature such as Analytic Network Process (ANP), Analytic Hierarchy Process (AHP), Best-Worst Method (BWM), Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS), Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Multi-Attributive Border Approximation area Comparison (MABAC) and others. AHP is one of widely used and most popular MCDM methods. AHP is based on pairwise comparisons and experts' judgments (Saaty, 2008). AHP divides a huge and complex problem into smaller and easier problems which can be solved easily and then combine these sub-solutions to obtain the final solution of the main problem (Otay *et al.*, 2017). Traditional AHP uses a linguistic scale of 1 to 9 with numerical values. However, according to Buckley (1985), a precise numerical representation of a linguistic term may not reflect the judgments in the minds of decision makers (DMs). For example, a linguistic assessment such as "Very Strong Significance" is expressed with a 7 on the traditional AHP scale. However, the DM's "Very Strong Significance" decision cannot be certain enough to assign a "7". With "Very Strong Significance", DM can

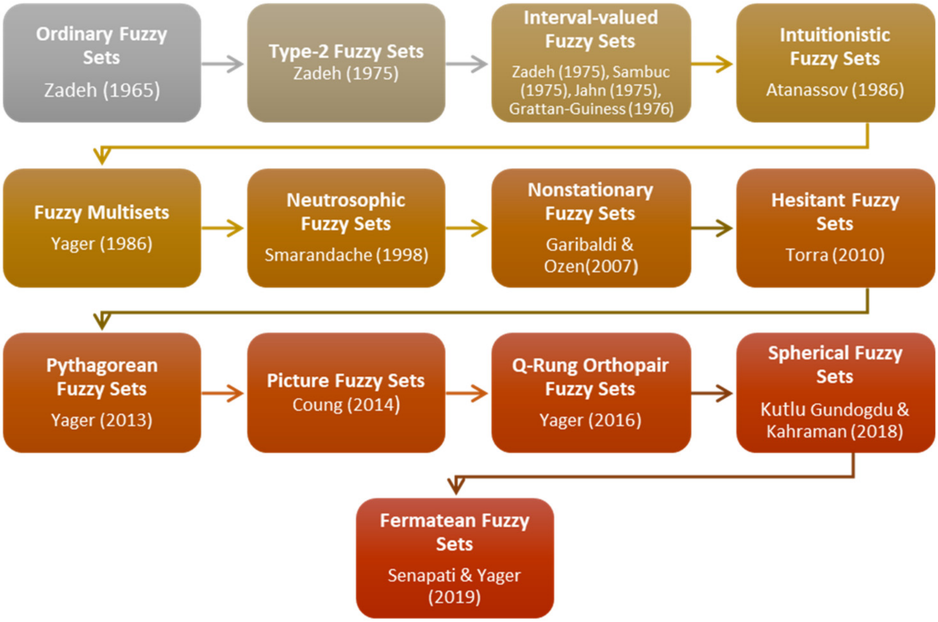

Fig. 1. Extension of fuzzy sets.

assign a corresponding fuzzy number such as (6.5, 7, 7.5). This may provide a better representation of the DM's assessment. Fuzzy sets are excellent tools for overcoming such uncertainty (Otay *et al.*, 2017). Fuzzy sets introduced by Zadeh (1965) are represented by membership degrees. Since its development, fuzzy sets have extended in various ways due to the lack of information and inability to handle the imprecise information of complex systems. Various extensions of ordinary fuzzy sets have been introduced in the literature to define membership functions in different ways (see Fig. 1). After type-2 fuzzy sets were introduced by Zadeh (1975), Intuitionistic fuzzy sets (IFSs) expressed with degrees of membership and non-membership have been proposed by Atannasov (1986). Later, Atannasov (1999) have introduced intuitionistic type-2 fuzzy sets (IFS2). After hesitant fuzzy sets (HFSs) were introduced by Torra (2010), IFS2 were extended by Yager (2013) to Pythagorean fuzzy sets (PFSs), which are represented by a larger area for membership degrees. After that, Yager (2017) introduced q-rung orthopair fuzzy sets, which is a general class of IFSs and PFSs. In IFSs the sum of membership and non-membership degrees should be at most one, in PFSs the sum of their squares should be at most one, and also for q-rung orthopair fuzzy sets, the sum of their qth power have to equal at most to one. Yager stated that as q increases, the range of acceptable orthopair increases, thus giving the user more freedom to express his belief about the degree of membership. When $q = 3$, Senapati and Yager (2020) have considered as fermatean fuzzy sets (FFSs) to q-rung orthopair fuzzy sets. They defined basic operations for the FFSs and introduced new score function and accuracy function for the ranking of FFSs. Besides, they developed a fermatean fuzzy TOPSIS method for handling the MCDM problem. Senapati and Yager (2019a) introduced Fermatean arithmetic mean operations, subtraction, division and developed a fermatean fuzzy weighted product model to solve the MCDM models. Then, Senapati and Yager (2019b) developed several fermatean fuzzy aggregation operators and proposed a MCDM approach by using new operators based on fermatean fuzzy conditions.

A more flexible definition of membership functions is needed to deal with uncertainty more effectively in fuzzy MCDM problems. FFSs are more suitable than other fuzzy set extensions to handle uncertainty by assigning the parameters of membership and non-membership grades to a larger domain.

In this study, we first develop a novel IVFF-AHP method, and then it has been implemented in selecting the best strategy for digital transformation strategies in the supply chain. It is known that in the literature there is no evaluation of digital transformation strategies in the supply chain with a MCDM method. Due to this lack of literature, the main motivation of study is the evaluation of digital transformation strategies in the supply chain and also the creation of a digital roadmap. The criteria used in the application have been determined by reviewing the articles and reports in the literature and taking into account the opinions of experts and systems in practice. The originality of this study comes from the development of a novel IVFF-AHP method and the first time evaluation as a MCDM problem of digital transformation strategies in the supply chain.

The rest of the paper is organized as follows: general information on digital transformation strategies is presented in Section 2. The preliminaries of intuitionistic, Pythagorean, and fermatean fuzzy sets are summarized and interval-valued fermatean fuzzy sets are presented in Section 3. Our proposed MCDM technique, the IVFF-AHP method, is given in Section 4. IVFF-AHP method is applied to the best supply chain digital transformation strategy selection problem in Section 5. Finally, the study is concluded in Section 6.

2. Digital Transformation Era and Strategies

Digital transformation is defined as the process of organizational change that digital technologies (such as big data analysis, cloud computing, internet of things, 3D printing) are accustomed to change, generating value in products of a business, interacting with its customers, partners, and suppliers, and competing in the global market. Digital transformation is a change and therefore every attempt of organizational change should be managed carefully (Agrawal and Narain, 2018). Digitizing the supply chain enables companies to meet customers' new requirements, supply-side challenges, and remaining expectations in efficiency improvement. Digitization brings a Supply Chain 4.0 that will be faster, more flexible, more detailed, more accurate, more efficient (Alicke *et al.*, 2016). Digital supply chains are capable of broad information availability and provide superior collaboration and communication between digital platforms, providing enhanced reliability, efficiency and agility (Raab and Griffin-Cryan, 2011). A successful digital transformation largely depends on the digital transformation of each partner in the value chain of organizations and all processes and information flows between these different partners. It also requires adopting a holistic view of the entire partner ecosystem.

The first-of-its-kind study, jointly conducted by CapGemini Consulting and GT Nexus, to specifically examine digital transformation across the entire value chain of supply chain networks surveyed 337 executives from large manufacturing and retail organizations in more than 20 different countries around the world. More than 75% of respondents said Digital Transformation is important or very important in their supply chain, and 70% of respondents said their organization has already initiated a formal Digital Supply Chain Transformation effort. In the survey, when executives were asked to comment on their level of satisfaction with the progress Digital Supply Chain Transformation efforts have made so far, one-third of executives said they were dissatisfied with their organization's progress towards Digital Transformation. Only 5% stated that they were very satisfied. As the main barriers to this situation, 44% of managers reported a general lack of awareness in their organization and 39% reported a lack of necessary skills in the workforce (Dougados and Felgendreher, 2016). Many organizations invest seriously to developed DSC in their institutions. According to a PwC study of more than 2 000 respondents, a third of them have started digitizing their supply chains, and 72 percent expect to do so five years from now. At the same time, organizations having on a large-scale digital supply chains and operations are to expect efficiency increases of 4.1 percent annually, while boosting revenue by 2.9 percent a year (Schrauf and Berttram, 2016).

2.1. *Literature Review*

Although there are many studies in the literature addressing digital transformation in the supply chain, there are no studies evaluating its strategies with a MCDM. Therefore, in this section, we reviewed the studies of digital transformation in supply chain to form the basis for our study. Xu (2014) gave important information about digital enterprise management required by decision-makers and managers in the organizations by focusing on digital enterprise and its managing. He also reviewed emerging trends and future directions, issues, and success factors of managing DSC. Uhl and Gollenia (2016) reviewed the combination of transformational capabilities and new digital skills to be developed. They also presented examples of a Digital Transformation Roadmap by introducing a set of different digital use cases related to supply chain management. Büyüközkan and Göçer (2018a) reviewed the state-of-the-art of the current DSC literature, detailing it from both academic and industrial perspectives. They also presented the main limitations and prospects in DSC, advantages, weaknesses, and limitations of individual methods. Büyüközkan and Göçer (2018b) proposed a new MCDM approach to evaluate the supplier selection process in the DSC environment. They presented a new framework that combines the interval-valued intuitionistic fuzzy (IVIF) AHP method to evaluate criterion weights and the Additive Ratio Assessment (ARAS) methodology to evaluate alternatives. Büyüközkan and Göçer (2019) used an approach that integrates PFSs into alternative DSC partner selection. Bienhaus and Haddud (2018) aimed to identify the effect of digitization on procurement and its role in the area of supply chain management. In the study, they also introduced potential obstacles to digitizing procurement and supply chains and ways to overcome them. Farahani *et al.* (2016a) presented an overview of the DSC management practices of leading companies in various industries, the DSC management concepts, and opportunities that arise from the application of digital technologies to supply chain management (SCM). Agrawal and Narain (2018) referred to its benefits by offering a framework of the digital supply chain. Scuotto *et al.* (2017) explained the relationship between multiple buyers and suppliers in the context of SMEs' DSC management. Farahani *et al.* (2016b) provided the creation of the DSC management agenda by presenting 17 DSC management use cases identified by expert interviews. Korpela *et al.* (2016) aimed to establish a DSC integration based on global standards. Bhargava *et al.* (2013) proposed a new based approach for protecting shared data in DSCs. Pundir *et al.* (2019) reviewed the suitability of complementary technologies such as IoT and Blockchain technology for DSC. Luthra and Mangla (2018) evaluated challenges to Industry 4.0 initiatives for supply chain sustainability in developing economies using an extensive literature review. Büyüközkan and Göçer (2017) presented an approach evaluating with intuitionistic fuzzy sets the supplier selection process in the DSC environment. Using the MOORA (Multi-Objective Optimization with Ratio Analysis) method, they realized a real case study to show the validity of the proposed approach. Alkan (2021) used the interval-valued Pythagorean fuzzy AHP method to assess the risks of digital transformation based on a sustainable supply chain. Tjahjono *et al.* (2017) purposed to provide a thought towards Supply Chain 4.0 by presenting a preliminary analysis of the impact of Industry 4.0 on SCM. Ivanov *et al.* (2019) reviewed how digital technologies and Industry 4.0 affect the ripple effect and performance of the supply chains. They presented the first study that connects information, business, analytics, engineering, and perspectives on digitalization and supply chain risks.

2.2. *The Technological Enablers of DSC*

Digital Supply Chain transformation is based on the full implementation of various new digital technologies. With the developing technologies, consumers, employees and business partners have more expectations, leading companies to develop more reliable and sensitive supply chains. Therefore, organizations need to adopt new technologies such as cloud, big data analytics, augmented reality, internet of things and 3D printing to keep up with digital transformation. These technologies enable the digitization of products and services, new business models and the digitization and integration of every link in an organization's value chain (i.e. engineering and manufacturing, product development and innovation, digital workplace, distribution and digital sales channels and customer relationship management) will also offer enormous benefits through making production more responsive to consumer demand, reducing costs, saving consumers' time and boosting employment (PwC Sweden, 2018; WTO, 2019). The faster these technologies develop in performance and cost, the faster they will make a change in SCM and will have a considerable impact on current and future SCM tasks (Kearney, 2015). The aim of the DSC is to completely integrate and make visible every aspect of the movement of goods and services. The most important technology that will fulfill this purpose of DSC is big data (PwC Sweden, 2018). Big data is considered as high velocity, high volume, and high variety information assets that demand cost-effective, innovative forms of information processing for decision making (Farahani *et al.*, 2020). Big data in DSC is to realize the necessary transparency by uncovering process interruptions and ensuring that changes are implemented quickly. Big data analytics provide better demand forecasting and planning, inventory planning and management, network, and routing optimization advanced procurement with collaborative optimization (Kearney, 2015; Alkan and Kahraman, 2021). Cloud computing is described as a style of computing in which scalable and flexible IT-enabled capabilities are presented as a service through internet technologies (Farahani *et al.*, 2020). Cloud computing creates diverse business networks to enable companies to fully and rapidly engage with supply chain stakeholders (Kearney, 2015). The Internet of Things (IoT) is a network of physical objects that includes embedded technology to communicate, perceive, or interact with their internal and external environments (Farahani *et al.*, 2020). IoT provides to open up to new business models and operational possibilities in the supply chains and respond to changing customer needs in real-time effectively. Tracking and tracing throughout the supply chain are provided through technologies underlying IoT such as Bluetooth, GSM (global system for mobile communication), and radio frequency identification (RFID) to rapidly evaluate and respond to changes in customer demand (WTO, 2019). Warehouse automation through advanced robotic technologies becomes much more holistic as some warehouses are fully connected to production loading points, so that all processes are carried out without manual intervention (Alicke *et al.*, 2016). A three-dimensional scanner (3D) is a device creating object models of them by capturing data about the appearance and shape of real-world objects (Farahani *et al.*, 2020). With 3D printing in the supply chain, the spare parts supply chain can be decreased to much fewer suppliers, even making own production possible. Thereby, 3D having an important impact on physical flows in the supply chain leads to faster delivery to the customer, lower labour unit and transport cost, and notably reduced inventory levels and costs in the supply chain (PwC Sweden, 2018). Augmented reality is defined as the situation that creates a new perception environment by combining computer-generated elements with the real world, in which users can interact (WTO, 2019). Augmented reality in the supply chain contributes to finding the right quantity of the right material much more efficiently by enabling better warehouse management (Kearney, 2015). Except for these technologies, GPS technology allows companies to take full control of shipping locations, while sensors control environmental conditions such as temperature and humidity and determine maintenance requirements (PwC Sweden, 2018). Autonomous and smart vehicles provide significant operational cost reductions in transportation and product handling, and also offer several benefits related to lower environmental costs and lead times (Alicke *et al.*, 2016).

2.3. *Key Challenges and Opportunities of Digital Supply Chain*

Supply chain managers who want to implement digital transformation in their SCMs ensure that they not only identify the challenges and opportunities their organizations face, but also consider the way suppliers, customers and other market partners interact with their organizations by enabling the digital transformation of the entire organization, its services and products (Kearney, 2015). In SCM, organizations should apply various steps that are necessary to deliver a product or service to customers. According to the supply chain council, these steps can be operated with the help of the SCOR model which includes the Plan, Source, Make, Deliver, Return processes (Büyüközkan and Göçer, 2018a). This model includes all processes that meet lower costs and faster customer demand, helping to support communication between supply chain partners and increase the efficiency of supply chain management (Uhl and Gollenia, 2016). Each of these elements is quickly being digitalized through technological innovation and thereby the chain becomes an integrated system working flawlessly. As a result, a digital supply chain strategy must consider the issues and success factors of digital transformation in the supply chain and examine it as a holistic approach to reap the full benefits of digitalization.

Organizations seeking to establish a DSC will face competitive extinction unless they develop clear strategies that respond to the opportunities presented in an all-digital environment. An organization that wants to generate and measure long-term value should integrate its digital initiatives into its overall supply chain strategy. Therefore, a digital supply chain strategy should be an integral part of a company's overall business model and organizational structure (Raab and Griffin-Cryan, 2011). Once the strategies are determined, companies must implement the DSC opportunities needed to carry out the transformation in their organizations. To ensure the effectiveness and efficiency of supply chains, the digital supply chain must be more agile and stronger by having the right people and skills, processes and tools in the right places. To achieve these goals, organizations need to work on such initiatives as focusing on better system and process standardization, create new business models, reconfigure demand forecasts for better interaction with the customer, enhancing sourcing capabilities in emerging markets and institutionalizing staff development better (Xu, 2014).

Developing strategies based on demand, people, technology, and new business models provide that all sections of the organizations fulfill the required changes to become more demand-driven, customer-focused, technology-savvy, and risk compliant. Organizations must develop demand-based strategies for digital transformation in supply chains. Through demand-based strategies, organizations can obtain real-time data by continuously communicating with customers. Human resources and skills-based strategies enable the development of people with various skills to achieve DSC results. Organizations should find people capable of collecting and analysing data to make better decisions and thus provide more customer-oriented growth solutions. IT and technology-based strategies help efficiently deploy knowledge and integrate information and communication technologies. New business models-based strategies enable changes in current business models of organizations for better customer interaction (Bailey *et al.*, 2017).

3. Preliminaries: Intuitionistic, Pythagorean, and Fermatean Fuzzy Sets

In this section, the basic concepts and the mathematical operations of PFSs, IFSs, and FFSs have been briefly introduced.

Table 1
The issues and success factors of digital transformation in supply chain.

Sharing information	DSC provides sharing information about demand, manufacturing, inventories, and logistics capacity, and thus it enables much closer integration with customers by boosting the agility of the entire chain (Raab and Griffin-Cryan, 2011; Alicke *et al.*, 2016; Schrauf and Berttram, 2016; Xu, 2014; Ivanov *et al.*, 2019; WTO, 2019).
Cross-functional relationship	Inter-functional cooperation between various elements in the organization provides to ensure the elimination of various bottlenecks, delays, or interruptions in the processes and to create a smooth flow within the organization (Raab and Griffin-Cryan, 2011; The Center for Global Enterprise, 2015; Farahani *et al.*, 2020; Alicke *et al.*, 2016; Schrauf and Berttram, 2016; Xu, 2014).
Adoption of advanced analytical tools	Adoption of advanced analytical tools provide to gain a better understanding and forecasting of the demand and accelerate the decision-making process (The Center for Global Enterprise, 2015; Farahani *et al.*, 2020; Schrauf and Berttram, 2016; Xu, 2014; Kearney, 2015; Gezgin *et al.*, 2017).
Supply chain visibility	Real-time visibility in the supply chain improves better DSC management by creating a coordinated end-to-end supply chain (Raab and Griffin-Cryan, 2011; Farahani *et al.*, 2020; Agrawal and Narain, 2018; Schrauf and Berttram, 2016).
Financial approach	Financial measurements enable quick execution of digital transformation efforts with less cost (The Center for Global Enterprise, 2015; Schrauf and Berttram, 2016; Kearney, 2015; Gezgin *et al.*, 2017).
Customer orientation	Customer orientation aims to offer personalized products by meeting customer expectations through end-to-end connectivity between suppliers and customers through cloud-based platforms (Alicke *et al.*, 2016; Schrauf and Berttram, 2016; Xu, 2014; Kearney, 2015; Gezgin *et al.*, 2017).
Training and skills development	DSC requires providing employees with the necessary digital supply chain management skills to ensure an end-to-end understanding of value chain mechanics in digital transformation (Schrauf and Berttram, 2016; Xu, 2014; Luthra and Mangla, 2018; Gezgin *et al.*, 2017).
Digital culture	Digital culture is necessary for the adoption of a cultural change in the thinking of each member in the organization to realize end-to-end digital transformation (Schrauf and Berttram, 2016; Luthra and Mangla, 2018).
Innovation	Digital supply chain helps a company strengthen business models through innovations in its designs and collaborates more effectively with both suppliers and customers (Farahani *et al.*, 2020; Alicke *et al.*, 2016; Schrauf and Berttram, 2016).
Standardization	Identify the roles, duties and responsibilities of all parties in the digital supply chain and ensure that the terms of all agreements are clearly defined and agreed upon, as well as adopt a single set of global standards that support data exchange, processes and capabilities (Farahani *et al.*, 2020; Xu, 2014; Luthra and Mangla, 2018; Kearney, 2015).
Automation	Automated operations facilitate the work of supply chain professionals and increase operational efficiency by allowing them to focus on more valuable tasks (Farahani *et al.*, 2020; Alicke *et al.*, 2016; Schrauf and Berttram, 2016; Xu, 2014; Kearney, 2015; Gezgin *et al.*, 2017).
Integration	Integration enables simultaneous management of information and processes with all stakeholders in digital supply chain (The Center for Global Enterprise, 2015; Farahani *et al.*, 2020; Alicke *et al.*, 2016; Schrauf and Berttram, 2016; Xu, 2014; Kearney, 2015; Gezgin *et al.*, 2017).
Flexibility	Digitalization in the supply chain allows easy adaptation to change circumstances and quickly assess changes in end-customer demand (Raab and Griffin-Cryan, 2011; Farahani *et al.*, 2020; Alicke *et al.*, 2016; Schrauf and Berttram, 2016; Kearney, 2015).
Enhanced response management	DSC increases the speed of responding to highly variable markets and changing customer needs (Farahani *et al.*, 2020; Alicke *et al.*, 2016; Schrauf and Berttram, 2016; Xu, 2014).
Security and privacy	Security and privacy stand for the tools used to transform a factory into a smarter factor and a supply chain into smarter value chains by avoiding security vulnerabilities increasing with digitalization in the supply chain (The Center for Global Enterprise, 2015; Luthra and Mangla, 2018; Kearney, 2015).

3.1. *Intuitionistic Fuzzy Sets (IFSs)*

Intuitionistic fuzzy sets proposed by Atannasov (1986) are an extension of the traditional fuzzy set theory. An IFS is defined by two membership values named as membership and non-membership that their sum is one or less than one.

Definition 3.1. Let X be a non-empty set. An IFS I in X is given by:

$$I = \{(x, \mu_I(x), \nu_I(x)) \mid x \epsilon X\}, \tag{1}$$

where the function $\mu_I : X \to [0, 1]$ and $\upsilon_I : X \to [0, 1]$ defines the membership and non-membership degrees of an element to the sets I with the condition that

$$0 \leqslant \mu_I(x) + \nu_I(x) \leqslant 1, \quad \text{for } \forall x \epsilon X. \tag{2}$$

The hesitancy degree is calculated as follows:

$$\pi_I(x) = 1 - \mu_I(x) - \nu_I(x). \tag{3}$$

Definition 3.2. Let $\tilde{A} = (\mu_{\tilde{A}}, \nu_{\tilde{A}})$ and $\tilde{B} = (\mu_{\tilde{B}}, \nu_{\tilde{B}})$ be two IFS, then the addition and multiplication operations on these two PFNs is calculated as follows:

$$\tilde{A} \oplus \tilde{B} = (\mu_{\tilde{A}} + \mu_{\tilde{B}} - \mu_{\tilde{A}}\mu_{\tilde{B}}, \nu_{\tilde{A}}\nu_{\tilde{B}}), \tag{4}$$

$$\tilde{A} \otimes \tilde{B} = (\mu_{\tilde{A}}\mu_{\tilde{B},} \nu_{\tilde{A}} + \nu_{\tilde{B}} - \nu_{\tilde{A}}\nu_{\tilde{B}}). \tag{5}$$

3.2. *Pythagorean Fuzzy Sets (PFSs)*

Pythagorean fuzzy sets (PFS) introduced as an extension of intuitionistic fuzzy set by Yager (2013) are defined two membership values named as membership and non-membership. In PFSs, the sum of membership and non-membership degrees assigned by decision-makers can exceed 1, but the sum of their squares must be at most 1. PFSs are defined in Definition 3.3.

Definition 3.3. Let X be a non-empty set. A Pythagorean fuzzy set P in X is an object having the form (Zhang and Xu, 2014):

$$P = \{\langle x, \mu_P(x), \nu_P(x)\rangle \mid x \epsilon X\}, \tag{6}$$

where the function $\mu_P : X \to [0, 1]$ defines the degree of membership and $\upsilon_P : X \to [0, 1]$ defines the degree of non-membership of the element $x \in X$ to P and it holds that:

$$0 \leqslant (\mu_P(x))^2 + (\nu_P(x))^2 \leqslant 1, \quad \text{for } \forall x \epsilon X. \tag{7}$$

The hesitancy degree is calculated as follows:

$$\pi_P(X) = \sqrt{1 - \mu_P(x)^2 - \nu_P(x)^2}. \tag{8}$$

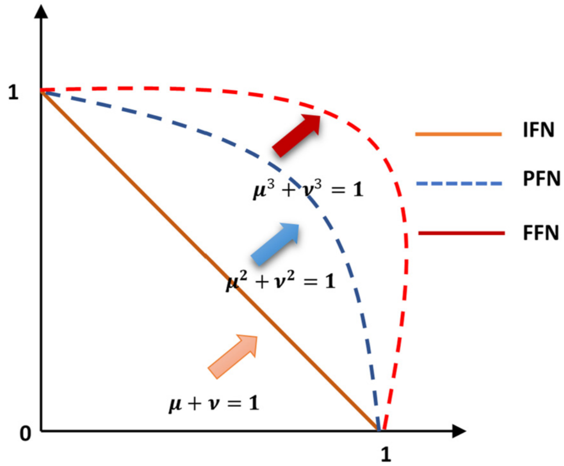

Fig. 2. Comparison of IFSs, PFSs and FFSs.

Definition 3.4. Let $P_1=(\mu_{P1},\nu_{P1})$ and $P_2=(\mu_{P2},\nu_{P2})$ be two PFNs, then the operations of these two PFNs are described as follows Zhang and Xu (2014):

$$P_1 \oplus P_2 = \left(\sqrt{\mu_{P1}^2+\mu_{P2}^2-\mu_{P1}^2\mu_{P2}^2}, \nu_{P1}\nu_{P2}\right), \tag{9}$$

$$P_1 \otimes P_2 = \left(\mu_{P1}\mu_{P2}, \sqrt{\nu_{P1}^2+\nu_{P2}^2-\nu_{P1}^2\nu_{P2}^2}\right). \tag{10}$$

3.3. *Fermatean Fuzzy Sets (FFSs)*

Yager (2017) introduced q-rung orthopair fuzzy sets, a general class of IFSs and PFSs. The sum of the qth power of membership and non-membersip degrees q-rung orthopair fuzzy sets is bounded with one. When $q = 3$, Senapati and Yager (2020) have called q-rung orthopair fuzzy sets as fermatean fuzzy sets (see Fig. 2).

Definition 3.5. Let X be a universe of discourse. A fermatean fuzzy set $\mathcal{F}$ in X is an object having the form (Senapati and Yager, 2020):

$$\mathcal{F} = \left\{\left\langle x, \mu_F(x), \nu_F(x)\right\rangle \middle| x \epsilon X\right\}, \tag{11}$$

where $\mu_F : X \to [0,1]$ and $\upsilon_F : X \to [0,1]$ which includes the circumstance

$$0 \leqslant \left(\mu_F(x)\right)^3 + \left(\nu_F(x)\right)^3 \leqslant 1 \tag{12}$$

for all $x \in X$. The numbers $\mu_F(x)$ and $\nu_F(x)$ indicate, respectively, the membership and non-membership degrees of the element x in the set $\mathcal{F}$.

For any FFS $\mathcal{F}$ and $x \in X$, the hesitancy degree is calculated as follows:

$$\pi_F(X) = \sqrt[3]{1-\mu_F(x)^3-\nu_F(x)^3}. \tag{13}$$

DEFINITION 3.6. Let $\mathcal{F} = (\mu_F, \nu_F)$, $\mathcal{F}_1 = (\mu_{F_1}, \nu_{F_1})$ and $\mathcal{F}_2 = (\mu_{F_2}, \nu_{F_2})$ be three FFSs, then their operations are described as follows Senapati and Yager (2020):

$$\mathcal{F}_1 \cap \mathcal{F}_2 = \left(\min\{\mu_{F_1}, \mu_{F_2}\}, \max\{\nu_{F_1}, \nu_{F_2}\}\right), \tag{14}$$

$$\mathcal{F}_1 \cup \mathcal{F}_2 = \left(\max\{\mu_{F_1}, \mu_{F_2}\}, \min\{\nu_{F_1}, \nu_{F_2}\}\right), \tag{15}$$

$$\mathcal{F}^c = (\nu_F, \mu_F).$$

DEFINITION 3.7. Let $\mathcal{F} = (\mu_F, \nu_F)$, $\mathcal{F}_1 = (\mu_{F_1}, \nu_{F_1})$ and $\mathcal{F}_2 = (\mu_{F_2}, \nu_{F_2})$ be three FFSs and $\lambda > 0$, then the operations of these three FFNs are defined as follows Senapati and Yager (2020):

$$\mathcal{F}_1 \oplus \mathcal{F}_2 = \left(\sqrt[3]{\mu_{F1}^3 + \mu_{F2}^3 - \mu_{F1}^3\mu_{F2}^3}, \nu_{F1}\nu_{F2}\right), \tag{16}$$

$$\mathcal{F}_1 \otimes \mathcal{F}_2 = \left(\mu_{F1}\mu_{F2}, \sqrt[3]{\nu_{F1}^3 + \nu_{F2}^3 - \nu_{F1}^3\nu_{F2}^3}\right), \tag{17}$$

$$\lambda\mathcal{F} = \left(\sqrt[3]{1 - \left(1 - \mu_F^3\right)^\lambda}, \nu_F^\lambda\right), \quad \lambda > 0, \tag{18}$$

$$\mathcal{F}^\lambda = \left(\mu_F^\lambda, \sqrt[3]{1 - \left(1 - \nu_F^3\right)^\lambda}\right), \quad \lambda > 0. \tag{19}$$

DEFINITION 3.8. Let $\mathcal{F}_i = (\mu_{F_i}, \nu_{F_i})$ $(i = 1, 2, \dots, n)$ be a set of FFNs and $w = (w_1, w_2, \dots, w_n)^T$ be weight vector of $\mathcal{F}_i$ with $\sum_{i=1}^n w_i = 1$, then a fermatean fuzzy weighted average (FFWA) operator is (Senapati and Yager, 2019b):

$$FFWA(\mathcal{F}_1, \mathcal{F}_2, \dots, \mathcal{F}_n) = \left(\sum_{i=1}^n w_i\mu_{\mathcal{F}_i}, \sum_{i=1}^n w_i\upsilon_{\mathcal{F}_i}\right). \tag{20}$$

DEFINITION 3.9. Let $\mathcal{F}_i = (\mu_{F_i}, \nu_{F_i})$ $(i = 1, 2, \dots, n)$ be a set of FFNs and $w = (w_1, w_2, \dots, w_n)^T$ be weight vector of $\mathcal{F}_i$ with $\sum_{i=1}^n w_i = 1$, then a fermatean fuzzy weighted geometric (FFWG) operator is (Senapati and Yager, 2019b):

$$FFWG(\mathcal{F}_1, \mathcal{F}_2, \dots, \mathcal{F}_n) = \left(\prod_{i=1}^n \mu_{\mathcal{F}_i}^{w_i}, \prod_{i=1}^n \upsilon_{\mathcal{F}_i}^{w_i}\right). \tag{21}$$

3.4. *Interval-Valued Fermatean Fuzzy Sets (IVFFSs)*

In this section, the mathematical operations of IVFFSs have been briefly presented (Jeevaraj, 2021).

DEFINITION 3.10. Let X be a fixed set. An IVFFSs $\tilde{\mathcal{F}}$ in X is an object having the form

$$\tilde{\mathcal{F}} = \left\{\left\langle x, \mu_{\tilde{\mathcal{F}}}(x), \nu_{\tilde{\mathcal{F}}}(x)\right\rangle \middle| x \epsilon X\right\}, \tag{22}$$

where $\mu_{\tilde{\mathcal{F}}}(x) \subseteq [0, 1]$ and $\upsilon_{\tilde{\mathcal{F}}}(x) \subseteq [0, 1]$ indicate the membership and non-membership degrees of the element $x \in X$ to the set $\tilde{\mathcal{F}}$, respectively. Also, for each $x \in X$, $\mu_{\tilde{\mathcal{F}}}(X)$

and $\upsilon_{\tilde{\mathcal{F}}}(X)$ are closed intervals and their lower and upper bounds are denoted by $\mu^L_{\tilde{\mathcal{F}}}(x)$, $\mu^U_{\tilde{\mathcal{F}}}(x)$, $\upsilon^L_{\tilde{\mathcal{F}}}(x)$, $\upsilon^U_{\tilde{\mathcal{F}}}(x)$, respectively. Therefore, $\tilde{\mathcal{F}}$ can also be expressed as follows:

$$\mu_{\tilde{\mathcal{F}}}(x) = \left[\mu^L_{\tilde{\mathcal{F}}}(x), \mu^U_{\tilde{\mathcal{F}}}(x)\right] \subseteq [0, 1], \tag{23}$$

$$\nu_{\tilde{\mathcal{F}}}(x) = \left[\upsilon^L_{\tilde{\mathcal{F}}}(x), \upsilon^U_{\tilde{\mathcal{F}}}(x)\right] \subseteq [0, 1], \tag{24}$$

where the expression is subject to the condition

$$0 \leqslant \left(\mu^U_{\tilde{\mathcal{F}}}(x)\right)^3 + \left(\upsilon^U_{\tilde{\mathcal{F}}}(x)\right)^3 \leqslant 1. \tag{25}$$

For every $x \in X$, $\pi_{\tilde{\mathcal{F}}}(x) = [\pi^L_{\tilde{\mathcal{F}}}(x), \pi^U_{\tilde{\mathcal{F}}}(x)]$ is called the hesitancy degree in IVFFSs, where

$$\pi^L_{\tilde{\mathcal{F}}}(x) = \sqrt[3]{1 - \left(\mu^U_{\tilde{\mathcal{F}}}(x)\right)^3 - \left(\upsilon^U_{\tilde{\mathcal{F}}}(x)\right)^3} \quad \text{and}$$

$$\pi^U_{\tilde{\mathcal{F}}}(x) = \sqrt[3]{1 - \left(\mu^L_{\tilde{\mathcal{F}}}(x)\right)^3 - \left(\upsilon^L_{\tilde{\mathcal{F}}}(x)\right)^3}.$$

Definition 3.11. Let $\tilde{\mathcal{F}} = ([\mu^L_{\tilde{\mathcal{F}}}, \ \mu^U_{\tilde{\mathcal{F}}}], [\upsilon^L_{\tilde{\mathcal{F}}}, \upsilon^U_{\tilde{\mathcal{F}}}])$, $\tilde{\mathcal{F}}_1 = ([\mu^L_{\tilde{\mathcal{F}}_1}, \ \mu^U_{\tilde{\mathcal{F}}_1}], [\upsilon^L_{\tilde{\mathcal{F}}_1}, \upsilon^U_{\tilde{\mathcal{F}}_1}])$ and $\tilde{\mathcal{F}}_2 = ([\mu^L_{\tilde{\mathcal{F}}_2}, \ \mu^U_{\tilde{\mathcal{F}}_2}], [\upsilon^L_{\tilde{\mathcal{F}}_2}, \upsilon^U_{\tilde{\mathcal{F}}_2}])$ be three FFSs and $\lambda > 0$, then their operations are described as follows:

$$\tilde{\mathcal{F}}_1 \oplus \tilde{\mathcal{F}}_2 = \left(\left[\begin{array}{l} \sqrt[3]{(\mu^L_{\tilde{\mathcal{F}}_1})^3 + (\mu^L_{\tilde{\mathcal{F}}_2})^3 - (\mu^L_{\tilde{\mathcal{F}}_1})^3(\mu^L_{\tilde{\mathcal{F}}_2})^3}, \\ \sqrt[3]{(\mu^U_{\tilde{\mathcal{F}}_1})^3 + (\mu^U_{\tilde{\mathcal{F}}_2})^3 - (\mu^U_{\tilde{\mathcal{F}}_1})^3(\mu^U_{\tilde{\mathcal{F}}_2})^3} \end{array}\right], \left[\upsilon^L_{\tilde{\mathcal{F}}_1}\upsilon^L_{\tilde{\mathcal{F}}_2}, \upsilon^U_{\tilde{\mathcal{F}}_1}\upsilon^U_{\tilde{\mathcal{F}}_2}\right]\right), \tag{26}$$

$$\tilde{\mathcal{F}}_1 \otimes \tilde{\mathcal{F}}_2 = \left(\left[\mu^L_{\tilde{\mathcal{F}}_1}\mu^L_{\tilde{\mathcal{F}}_2}, \mu^U_{\tilde{\mathcal{F}}_1}\mu^U_{\tilde{\mathcal{F}}_2}\right], \left[\begin{array}{l} \sqrt[3]{(\upsilon^L_{\tilde{\mathcal{F}}_1})^3 + (\upsilon^L_{\tilde{\mathcal{F}}_2})^3 - (\upsilon^L_{\tilde{\mathcal{F}}_1})^3(\upsilon^L_{\tilde{\mathcal{F}}_2})^3}, \\ \sqrt[3]{(\upsilon^U_{\tilde{\mathcal{F}}_1})^3 + (\upsilon^U_{\tilde{\mathcal{F}}_2})^3 - (\upsilon^U_{\tilde{\mathcal{F}}_1})^3(\upsilon^U_{\tilde{\mathcal{F}}_2})^3} \end{array}\right]\right), \tag{27}$$

$$\lambda\tilde{\mathcal{F}} = \left(\left[\sqrt[3]{1 - \left(1 - \left(\mu^L_{\tilde{\mathcal{F}}}\right)^3\right)^\lambda}, \sqrt[3]{1 - \left(1 - \left(\mu^U_{\tilde{\mathcal{F}}}\right)^3\right)^\lambda}\right], \left[\left(\upsilon^L_{\tilde{\mathcal{F}}}\right)^\lambda, \left(\upsilon^U_{\tilde{\mathcal{F}}}\right)^\lambda\right]\right), \tag{28}$$

$$\tilde{\mathcal{F}}^\lambda = \left(\left[\left(\mu^L_{\tilde{\mathcal{F}}}\right)^\lambda, \left(\mu^U_{\tilde{\mathcal{F}}}\right)^\lambda\right], \left[\sqrt[3]{1 - \left(1 - \left(\upsilon^L_{\tilde{\mathcal{F}}}\right)^3\right)^\lambda}, \sqrt[3]{1 - \left(1 - \left(\upsilon^U_{\tilde{\mathcal{F}}}\right)^3\right)^\lambda}\right]\right). \tag{29}$$

Definition 3.12. Let $\tilde{\mathcal{F}}_i = ([\mu^L_{\tilde{\mathcal{F}}_i}, \mu^U_{\tilde{\mathcal{F}}_i}], [\upsilon^L_{\tilde{\mathcal{F}}_i}, \upsilon^U_{\tilde{\mathcal{F}}_i}])$ $(i = 1, 2, \dots, n)$ be a set of IVFFSs and $w = (w_1, w_2, \dots, w_n)^T$ be a weight vector of $\mathcal{F}_i$ with $\sum_{i=1}^n w_i = 1$, then an interval-valued fermatean fuzzy weighted average (IVFFWA) operator is a mapping IVFFWA: $\tilde{\mathcal{F}}^n \to \tilde{\mathcal{F}}$, where

$$
\begin{aligned}
&IVFFWA(\tilde{\mathcal{F}}_1, \tilde{\mathcal{F}}_2, \ldots, \tilde{\mathcal{F}}_n) \\
&\quad = \left(\left[\sqrt[3]{\left(1-\prod_{i=1}^{n}\left(1-\left(\mu_{\tilde{\mathcal{F}}_i}^{L}\right)^3\right)^{w_i}\right)}, \sqrt[3]{\left(1-\prod_{i=1}^{n}\left(1-\left(\mu_{\tilde{\mathcal{F}}_i}^{U}\right)^3\right)^{w_i}\right)}\right],\right. \\
&\qquad \left.\times \left[\prod_{i=1}^{n}\left(\upsilon_{\tilde{\mathcal{F}}_i}^{L}\right)^{w_i}, \prod_{i=1}^{n}\left(\upsilon_{\tilde{\mathcal{F}}_i}^{U}\right)^{w_i}\right]\right). \qquad (30)
\end{aligned}
$$

Definition 3.13. Let $\tilde{\mathcal{F}}_i = ([\mu_{\tilde{\mathcal{F}}_i}^{L}, \mu_{\tilde{\mathcal{F}}_i}^{U}], [\upsilon_{\tilde{\mathcal{F}}_i}^{L}, \upsilon_{\tilde{\mathcal{F}}_i}^{U}])$ $(i = 1, 2, \ldots, n)$ be a set of IVFFSs and $w = (w_1, w_2, \ldots, w_n)^T$ be a weight vector of $\tilde{\mathcal{F}}_i$ with $\sum_{i=1}^{n} w_i = 1$, then an interval-valued fermatean fuzzy weighted geometric (IVFFWG) operator is a mapping IVFFWG: $\tilde{\mathcal{F}}^n \rightarrow \tilde{\mathcal{F}}$, where

$$
\begin{aligned}
&IVFFWG(\tilde{\mathcal{F}}_1, \tilde{\mathcal{F}}_2, \ldots, \tilde{\mathcal{F}}_n) \\
&\quad = \left(\left[\prod_{i=1}^{n}\left(\mu_i^{L}\right)^{w_i}, \prod_{i=1}^{n}\left(\mu_i^{U}\right)^{w_i}\right],\right. \\
&\qquad \left.\times \left[\sqrt[3]{\left(1-\prod_{i=1}^{n}\left(1-\left(\upsilon_{\tilde{\mathcal{F}}_i}^{L}\right)^3\right)^{w_i}\right)}, \sqrt[3]{\left(1-\prod_{i=1}^{n}\left(1-\left(\upsilon_{\tilde{\mathcal{F}}_i}^{U}\right)^3\right)^{w_i}\right)}\right]\right). \qquad (31)
\end{aligned}
$$

Definition 3.14. Deffuzzification of $\tilde{\mathcal{F}}_i = ([\mu_{\tilde{\mathcal{F}}_i}^{L}, \mu_{\tilde{\mathcal{F}}_i}^{U}], [\upsilon_{\tilde{\mathcal{F}}_i}^{L}, \upsilon_{\tilde{\mathcal{F}}_i}^{U}])$ $(i = 1, 2, \ldots, n)$ is given as in Eq. (32):

$$
\mathrm{Deff}(\tilde{\mathcal{F}}_i) = \begin{cases}
\dfrac{1+|(\mu_i^L)^3-(\upsilon_i^L)^3|+1+|(\mu_i^U)^3-(\upsilon_i^U)^3|-(\pi_{ij}^L)^3-(\pi_{ij}^U)^3}{4} \times 10, \\
EI \leqslant IVFFN \leqslant CHI, \\
\dfrac{1}{\left(\frac{1+|(\mu_{ij}^L)^3-(\upsilon_{ij}^L)^3|+1+|(\mu_{ij}^U)^3-(\upsilon_{ij}^U)^3|-(\pi_{ij}^L)^3-(\pi_{ij}^U)^3}{4}\times 10\right)}, \\
SLI \leqslant IVFFN \leqslant CLI.
\end{cases} \qquad (32)
$$

This defuzzification operation is based on Saaty's classical 1–9 scale so that the defuzzification produces values between 1–9 for $EI \leqslant IVFFN \leqslant CHI$ and 1/9–1 for $SLI \leqslant IVFFN \leqslant CLI$.

4. A Novel Fermatean Fuzzy Analytic Hierarchy Process Method

AHP, which is one of the most used MCDM methods in literature, has been introduced by Saaty in 1980 and the method has a structured form used to weight criteria and make decisions in complex MCDM problems. But, in the classic AHP method, decision-makers' evaluations in uncertainty cases can not be expressed. Therefore, classic AHP has been extended to fuzzy AHP to model the uncertainty in human judgment and preference. Fuzzy AHP has been used to deal with many MCDM problems in studies in the literature and the method has emerged in different forms with new extensions of fuzzy sets. Van Laarhoven and Pedrycz (1983) used triangular fuzzy numbers as the first extension of fuzzy AHP to calculate fuzzy weights and fuzzy alternative scores. Buckley (1985) used the geometric mean method based on the trapezoidal fuzzy numbers to calculate the fuzzy weights and fuzzy alternative scores. Chang (1986) proposed a novel approach for the synthetic extent values of the pairwise comparison scale of fuzzy AHP by using the triangular fuzzy numbers. Kahraman *et al.* (2016) developed both interval-valued type-2 fuzzy AHP method and a new ranking method based on type-2 fuzzy sets by handling a supplier selection problem. Sadiq and Tesfamariam (2009) developed intuitionistic fuzzy AHP to handle vagueness and uncertainties in decision-making process. Wu *et al.* (2013) developed a score function based on interval-valued intuitionistic fuzzy numbers (IVIFNs) and proposed a new interval-valued intuitionistic fuzzy AHP (IVIF-AHP) method for MCDM problems. Öztaysi *et al.* (2015) developed the hesitant fuzzy AHP where the evaluations of experts are aggregated by ordered weighted averaging (OWA) operator. Gul (2018) proposed a new approach integrated Pythagorean fuzzy AHP and fuzzy VIKOR for risk assessment in the field of occupational health and safety. The Pythagorean fuzzy AHP has been used for weighting of the risk parameters. Then, fuzzy VIKOR has been applied to prioritize the hazards. Büyüközkan and Göçer (2019) proposed a new approach integrating AHP and complex proportional assessment (COPRAS) based on Pythagorean fuzzy sets to evaluate the digital supply chain partner selection. Karasan *et al.* (2019) developed a new Pythagorean fuzzy AHP method and compared it with ordinary fuzzy AHP, revealing that the developed method produces consistent results that better represent the uncertainty of the decision-making environment. Abdel-Basset *et al.* (2017) proposed a neutrosophic AHP method by using the triangular neutrosophic numbers for each pairwise comparison judgment. Bolturk and Kahraman (2018) proposed a new interval-valued neutrosophic AHP method and interval-valued neutrosophic AHP (IVN-AHP) based on cosine similarity measures. The proposed methods provide a scoring procedure for pairwise comparison matrices based on neutrosophic numbers. Garg *et al.* (2021) developed complex interval-valued q-rung orthopair fuzzy sets (CIVq-ROFSs) and then developed averaging aggregation operator and geometric aggregation operators based on CIVq-ROFSs. They proposed AHP and TOPSIS methods based on CIVq-ROFSs. Kutlu Gündoğdu *et al.* (2021) introduced a new hybrid picture fuzzy analytic hierarchy process and linear assignment model. The hybrid picture fuzzy AHP-linear assignment model validated with a comparative analysis. Mathew *et al.* (2020) presented a novel approach integrating AHP and TOPSIS based on spherical fuzzy sets. They proposed a novel spherical fuzzy geometric mean formula for calculating the spherical fuzzy criteria weights and also presented a novel eleven-point spherical fuzzy linguistic term scale. Kahraman *et al.* (2020) presented a literature review of studies on the integration of fuzzy AHP with other fuzzy multi-criteria methods. Duan *et al.* (2021) presented some fundamental operations based on q-rung orthopair double hierarchy linguistic term sets (q-RODHLTS) and developed AHP method under q-RODHLTS. The distribution of fuzzy AHP publications from past to present analysed by using the Scopus database is illustrated in Fig. 3. As it is seen, engineering is the most researched scientific field in the literature, followed by computer science, mathematics and business, management and accounting research fields.

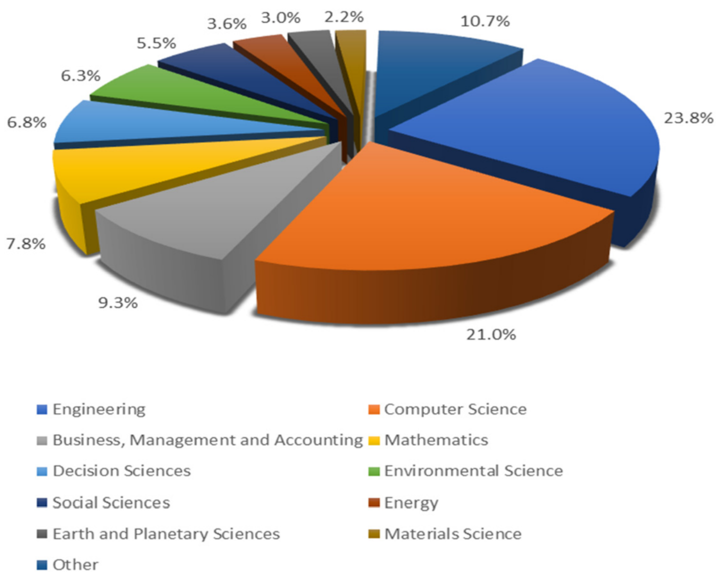

Fig. 3. Percentages of fuzzy AHP studies based on application areas.

4.1. *Proposed Method: IVFF-AHP*

Fermatean fuzzy sets, which are the extension of ordinary fuzzy sets, have been introduced by Senapati and Yager (2020). No study integrating FFSs with the AHP method has been performed in the literature. The steps of the proposed IVFF-AHP method whose flow chart is illustrated in Fig. 4 are given as follows:

Step 1: Construct the hierarchical structure by determining the criteria and alternatives.

Determine objective, decision criteria, and alternatives for the given problem. The set $A_i = \{A_1, A_2, \dots, A_n\}$, having $i = 1, 2, \dots, n$ alternatives, is evaluated by m decision criteria of set $C_j = \{C_1, C_2, \dots, C_m\}$, with $j = 1, 2, \dots, m$. Let $w_j = (w_1, w_2, \dots, w_m)$ be the vector set used for defining the criteria weights, where $w_j > 0$ and $\sum_{j=1}^{n} w_j = 1$. Table 2 presents linguistic terms and their corresponding interval-valued fermatean fuzzy numbers (IVFFNs).

Step 2: Construct the pairwise comparison matrix $Z = (z_{ij})_{m\times m}$ based on the opinions of experts given in Table 2.

$$Z = \begin{bmatrix} 1 & z_{12} & \cdots & z_{1m} \\ z_{21} & 1 & \cdots & z_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \cdots & 1 \end{bmatrix}, \quad \text{where } z_{ij} = \left\langle [\mu_{ij}^L, \mu_{ij}^U], [\nu_{ij}^L, \nu_{ij}^U] \right\rangle. \tag{33}$$

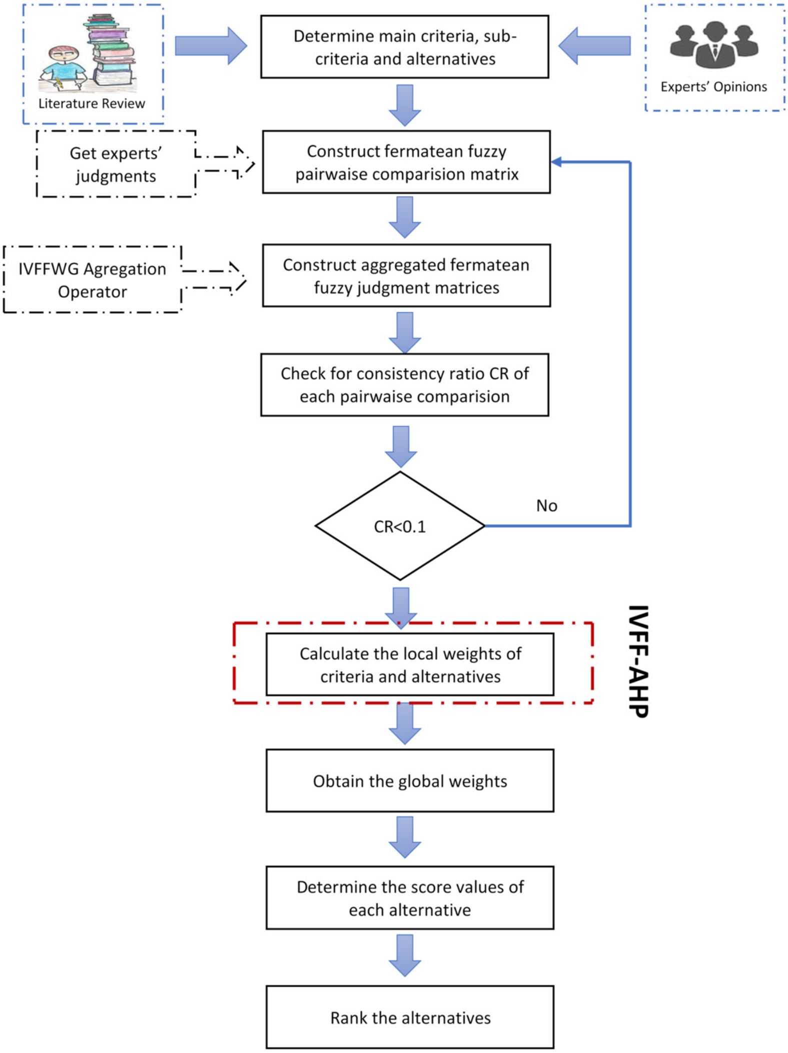

Fig. 4. Flowchart of the proposed method.

Step 3: Check for the consistency of each pairwise comparison matrix (Z). Here, to measure the consistency of expert judgments, match the crisp numbers obtained after defuzzifying to IVFFNs given in Table 2 based on Saaty's scale. Then, apply the Saaty's classical consistency process.

Step 4: Aggregate the judgments of experts.

The pairwise comparison matrix constituted for each expert is aggregated by using *IVFFWG* aggregation operator. Let $E_k = \{E_1, E_2, \ldots, E_k\}$, with $k = 1, 2, \ldots, K$, de-

Table 2
Linguistic terms and IVFFN equivalents.

Linguistic terms	IVFFN equivalents			
	μ_L	μ_U	υ_L	υ_U
Certainly High Importance (CHI)	0.95	1	0	0
Very High Importance (VHI)	0.8	0.9	0.1	0.2
High Importance (HI)	0.7	0.8	0.2	0.3
Slightly More Importance (SMI)	0.6	0.65	0.35	0.4
Equally Importence (EI)	0.5	0.5	0.5	0.5
Slightly Less Importance (SLI)	0.35	0.4	0.6	0.65
Low Importance (LI)	0.2	0.3	0.7	0.8
Very Low Importance (VLI)	0.1	0.2	0.8	0.9
Certainly Low Importance (CLI)	0	0	0.95	1

note the set of experts having influence weights w_k for each E_k; $\sum_{k=1}^{K} w_k = 1$.

$$\begin{aligned} &IVPFWG(z_1, z_2, \dots, z_k) \\ &= \left(\left[\prod_{k=1}^{K} (\mu_k^L)^{w_k}, \prod_{k=1}^{K} (\mu_k^U)^{w_k}\right],\right. \\ &\quad \times \left.\left[\sqrt[3]{\left(1-\prod_{k=1}^{K}\left(1-(\upsilon_k^L)^3\right)^{w_k}\right)}, \sqrt[3]{\left(1-\prod_{k=1}^{K}\left(1-(\upsilon_k^U)^3\right)^{w_k}\right)}\right]\right). \end{aligned} \tag{34}$$

Step 5: Find the differences matrix $D = (d_{ij})_{m \times m}$ between lower and upper points of the membership and non-membership functions using Eqs. (35) and (36):

$$d_{ij}^L = (\mu_{ij}^L)^3 - (\nu_{ij}^U)^3, \tag{35}$$

$$d_{ij}^U = (\mu_{ij}^U)^3 - (\nu_{ij}^L)^3. \tag{36}$$

Step 6: Find the interval multiplicative matrix $S = (s_{ij})_{m \times m}$ Eqs. (37) and (38):

$$s_{ij}^L = \sqrt[3]{1000^{d_{ij}^L}}, \tag{37}$$

$$s_{ij}^U = \sqrt[3]{1000^{d_{ij}^U}}. \tag{38}$$

Step 7: Obtain the indeterminacy value $T = (t_{ij})_{m \times m}$ of the z_{ij} using Eq. (39):

$$t_{ij} = 1 - (\mu_{ij_U}^3 - \mu_{ij_L}^3) - (\nu_{ij_U}^3 - \nu_{ij_L}^3). \tag{39}$$

Step 8: Multiply the indeterminacy degrees with $S = (s_{ij})_{m \times m}$ matrix to obtain the matrix of unnormalized weights $R = (r_{ij})_{m \times m}$ using Eq. (40):

$$r_{ij} = \left(\frac{s_{ij}^L + s_{ij}^U}{2}\right) t_{ij}. \tag{40}$$

Step 9. Obtain the normalized priority weights w_i by using Eq. (41):

$$w_i = \frac{\sum_{j=1}^{m} r_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{m} r_{ij}}. \tag{41}$$

Step 10. Rank the alternatives based on the normalized priority weights obtained in Step 9.

5. Application

5.1. *Problem Definition*

With the rapid advances in technology, digitalization has become an increasingly important issue investigated and discussed by academics and industries around the world. Currently, it has the potential to affect all sectors including supply chain and logistics. Thus, "digital supply chain" or "supply chain 4.0" has been introduced in the industrial world. Although many organizations have initiated a digital transformation in supply chains, they have not tackled it as a holistic approach to their DSC. This situation has caused delays in the progress of DSC until now. Hence, the biggest obstacle to successful digital transformation in the supply chain has been the lack of digital strategies in organizations. There has been a need to develop a framework and create awareness for the successful implementation of digital supply chain strategies. Due to this requirement emerging, organizations are required to evaluate their strategies according to certain criteria and they should use an MCDM method.

5.2. *Problem Solution*

In this section, the digital transformation strategies in the supply chain are evaluated by utilizing the proposed method and it is aimed to choose the best strategy among various alternatives. A decision-making group of three experts is formed to evaluate the strategies using the proposed method. In a fuzzy environment, three decision makers, abbreviated as E1, E2 and E3, are selected, consisting of academicians who are experts in multi-criteria decision making. The weights of the decision makers are considered equal because they have the same level of experience. As a result of expert opinions and evaluation of the studies in the literature, three main criteria, fifteen sub-criteria and four alternatives have been determined for the strategies required for digital transformation in the supply chain. The determined main criteria are *DC- Digital Competence, O- Organizational, and M-Management*. The sub-criteria are listed as *DC1- Digital Culture*, *DC2- Security and Privacy*, *DC3- Automation*, *DC4- Standardization*, *DC5- Innovation*, *O1- Sharing Information*, *O2- Cross-Functional Relationship*, *O3- Integration*, *O4- Training and Skills Development*, *M1- Adoption of Advanced Analytical Tools*, *M2- Supply Chain Visibility*, *M3-Financial Orientation*, *M4- Customer Orientation*, *M5-Flexibility*, and *M6- Enhanced Response*. Alternative strategies are *A1- Human Resource Management and Talent-Based Strategies*, *A2- Demand-Based Strategies*, *A3- New Business Models-Based Strategies*,

Table 3
Pairwise comparison judgments for the main criteria.

	E1			E2			E3		
	DC	O	M	DC	O	M	DC	O	M
DC	EI	SMI	SLI	EI	SMI	SLI	EI	HI	SLI
O	SLI	EI	LI	SLI	EI	VLI	LI	EI	VLI
M	SMI	HI	EI	SMI	VHI	EI	SMI	VHI	EI
CR	0.033			0.006			0.056		

and *A4- Technology and IT-Based Strategies*. Fig. 5 illustrates this hierarchical structure involving the main criteria, sub-criteria, and alternatives. These alternatives and criteria are evaluated by constructing pairwise comparison matrices through linguistic terms given in Table 2 by three experts. The pairwise comparison matrices consisting of linguistic terms for the main criteria, sub-criteria, and alternatives are presented with the consistency ratio in Tables 3–21. The consistency ratios of the pairwise comparison matrices are calculated using the linguistic scale and corresponding numerical values given in Table 2. Due to space constraints, the next steps of the developed method are shown on the main criteria. After linguistic expressions in the pairwise comparison, matrices are converted to IVFFNs using the relevant scale, each expert's assessment is aggregated with the IVFFWG operator. Table 22 presents the aggregated IVFF values of the main criteria. Then, IVFF-AHP is used to obtain the weights of criteria and alternatives. Table 23 gives the difference matrix $D = (d_{ij})_{m\times m}$ between lower and upper values of the membership and non-membership degrees calculated based on Eqs. (35) and (36). The interval multiplicative matrix $S = (s_{ij})_{m\times m}$ given in Table 24 is calculated based on Eqs. (37) and (38) in Step 6. The matrix of weights before normalization $R = (r_{ij})_{m\times m}$ presented in Table 25 is obtained based on Eq. (40) in Step 8 by using the indeterminacy values given in Eq. (39). Then, the priority weights of each criterion obtained by using Eq. (41) in Step 9 and the final overall criteria weights are presented in Table 26. The overall criteria weights are obtained by multiplying the weights of the related main criteria and sub-criteria. Table 27 presents the priority weights of the alternatives according to the evaluation criteria. Finally, according to score values and ranking of alternatives demonstrated in Table 28, A2 is selected as the most suitable alternative. *Demand-Based Strategies* should be adapted with the largest priority, followed by *New Business Models-Based Strategies*, *Technology and IT-Based Strategies*, and *Human Resource Management* and *Talent-Based Strategies*.

5.3. *Sensitivity Analysis*

A sensitivity analysis is performed to observe the effects of possible changes in the main criterion weights on the prioritization of digital transformation strategies in the supply chain. In this stage, the different final rankings of alternatives are observed as given in Fig. 6. The X-axis represents the change between CHI and CLI of the main criterion weight for four alternatives while Y-axis represents the ranking of alternatives. In this analysis, we change the weights of a certain criterion for each expert between CHI and CLI while the other criteria weights are fixed. For instance, when the weight of *organizational*

Table 4
Evaluation of the sub-criteria according to the main criterion digital competence.

	E1					E2					E3				
	DC1	DC2	DC3	DC4	DC5	DC1	DC2	DC3	DC4	DC5	DC1	DC2	DC3	DC4	DC5
DC1	EI	VHI	HI	VHI	SMI	EI	HI	SMI	VHI	SMI	EI	HI	SMI	VHI	EI
DC2	VLI	EI	LI	SMI	LI	LI	EI	LI	EI	LI	LI	EI	SLI	SMI	VLI
DC3	LI	HI	EI	HI	SLI	SLI	HI	EI	VHI	EI	SLI	SMI	EI	HI	SLI
DC4	VLI	SLI	LI	EI	VLI	VLI	EI	VLI	EI	VLI	VLI	SLI	LI	EI	VLI
DC5	SLI	HI	SMI	VHI	EI	SLI	HI	EI	VHI	EI	EI	VHI	SMI	VHI	EI
CR	0.098					0.047					0.035				

Table 5
Evaluation of the sub-criteria according to the main criterion organizational.

	E1				E2				E3			
	O1	O2	O3	O4	O1	O2	O3	O4	O1	O2	O3	O4
O1	EI	HI	EI	HI	EI	HI	SLI	VHI	EI	SMI	SLI	HI
O2	LI	EI	LI	SLI	LI	EI	LI	SMI	SLI	EI	LI	SMI
O3	EI	HI	EI	HI	SMI	HI	EI	VHI	SMI	HI	EI	VHI
O4	LI	SMI	LI	EI	VLI	SLI	VLI	EI	LI	SLI	VLI	EI
CR	0.059				0.086				0.044			

Table 6
Evaluation of the sub-criteria according to the main criterion management.

	E1						E2						E3					
	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6
M1	EI	SMI	CHI	EI	VHI	HI	EI	SMI	CHI	EI	HI	SMI	EI	EI	VHI	SLI	HI	SMI
M2	SLI	EI	VHI	SLI	HI	HI	SLI	EI	VHI	EI	HI	SMI	EI	EI	VHI	SLI	VHI	HI
M3	CLI	VLI	EI	VLI	SLI	SLI	CLI	VLI	EI	VLI	SLI	LI	VLI	VLI	EI	CLI	SLI	SLI
M4	EI	SMI	VHI	EI	VHI	HI	EI	EI	VHI	EI	VHI	HI	SMI	SMI	CHI	EI	HI	SMI
M5	VLI	LI	SMI	VLI	EI	SLI	LI	LI	SMI	VLI	EI	SLI	LI	VLI	SMI	LI	EI	EI
M6	LI	LI	SMI	LI	SMI	EI	SLI	SLI	HI	LI	SMI	EI	SLI	LI	SMI	SLI	EI	EI
CR	0.055						0.046						0.05					

Table 7
Evaluation of the alternatives according to the sub-criterion digital culture.

DC1	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	VHI	HI	EI	EI	HI	HI	SMI	EI	VHI	HI	SLI
A2	VLI	EI	LI	LI	LI	EI	SLI	LI	VLI	EI	SLI	VLI
A3	LI	HI	EI	SLI	LI	SMI	EI	SLI	LI	SMI	EI	LI
A4	EI	HI	SMI	EI	SLI	HI	SMI	EI	SMI	VHI	HI	EI
CR	0.079				0.075				0.086			

criterion with respect to *digital competence* criterion is changed between CHI and CLI, A2 has always placed in the first rank; when the weight of *management* criterion with respect

Table 8
Evaluation of the alternatives according to the sub-criterion security and privacy.

DC2	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	SLI	LI	CLI	EI	SLI	LI	CLI	EI	LI	SLI	CLI
A2	SMI	EI	SLI	VLI	SMI	EI	LI	VLI	HI	EI	SMI	LI
A3	HI	SMI	EI	LI	HI	HI	EI	SLI	SMI	SLI	EI	VLI
A4	CHI	VHI	HI	EI	CHI	VHI	SMI	EI	CHI	HI	VHI	EI
CR	0.064				0.067				0.064			

Table 9
Evaluation of the alternatives according to the sub-criterion automation.

DC3	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	VLI	VLI	CLI	EI	LI	LI	CLI	EI	VLI	VLI	CLI
A2	VHI	EI	EI	LI	HI	EI	SMI	SLI	VHI	EI	EI	LI
A3	VHI	EI	EI	LI	HI	SLI	EI	SLI	VHI	EI	EI	SLI
A4	CHI	HI	HI	EI	CHI	SMI	SMI	EI	CHI	HI	SMI	EI
CR	0.09				0.071				0.068			

Table 10
Evaluation of the alternatives according to the sub-criterion standardization.

DC4	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	SLI	LI	LI	EI	LI	LI	VLI	EI	SLI	LI	LI
A2	SMI	EI	SLI	LI	HI	EI	SLI	LI	SMI	EI	LI	LI
A3	HI	SMI	EI	SLI	HI	SMI	EI	SLI	HI	HI	EI	EI
A4	HI	HI	SMI	EI	VHI	HI	SMI	EI	HI	HI	EI	EI
CR	0.075				0.093				0.059			

Table 11
Evaluation of the alternatives according to the sub-criterion innovation.

DC5	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	VLI	VLI	LI	EI	CLI	CLI	VLI	EI	LI	VLI	VLI
A2	VHI	EI	EI	SMI	CHI	EI	EI	HI	HI	EI	SLI	SLI
A3	VHI	EI	EI	SMI	CHI	EI	EI	HI	VHI	SMI	EI	EI
A4	HI	SLI	SLI	EI	VHI	LI	LI	EI	VHI	SMI	EI	EI
CR	0.028				0.093				0.028			

to *organizational* criterion is also changed between CHI and CLI, A2 has been always observed in the first rank similarly. Unlike the others, when the weight of *management* criterion with respect to *digital competence* criterion is changed between CHI and CLI, A4 has only placed in the first rank while its weight is CHI and A2 has been observed as the best alternative in other linguistic weights. Sensitivity analysis shows that the main

Table 12
Evaluation of the alternatives according to the sub-criterion sharing information.

O1	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	LI	SLI	HI	EI	VLI	LI	SMI	EI	VLI	VLI	HI
A2	HI	EI	SMI	CHI	VHI	EI	SMI	VHI	VHI	EI	EI	CHI
A3	SMI	SLI	EI	VHI	HI	SLI	EI	HI	VHI	EI	EI	CHI
A4	LI	CLI	VLI	EI	SLI	VLI	LI	EI	LI	CLI	CLI	EI
CR	0.065				0.088				0.094			

Table 13
Evaluation of the alternatives according to the sub-criterion cross-functional relationship.

O2	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	SLI	SLI	HI	EI	LI	SLI	HI	EI	SLI	LI	HI
A2	SMI	EI	EI	CHI	HI	EI	SMI	CHI	SMI	EI	SLI	VHI
A3	SMI	EI	EI	CHI	SMI	SLI	EI	VHI	HI	SMI	EI	VHI
A4	LI	CLI	CLI	EI	LI	CLI	VLI	EI	LI	VLI	VLI	EI
CR	0.012				0.065				0.091			

Table 14
Evaluation of the alternatives according to the sub-criterion integration.

O3	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	SLI	EI	HI	EI	SLI	SMI	HI	EI	SLI	SMI	VHI
A2	SMI	EI	SMI	VHI	SMI	EI	SMI	VHI	SMI	EI	HI	VHI
A3	EI	SLI	EI	VHI	SLI	SLI	EI	HI	SLI	LI	EI	HI
A4	LI	VLI	VLI	EI	LI	VLI	LI	EI	VLI	VLI	LI	EI
CR	0.045				0.086				0.091			

Table 15
Evaluation of the alternatives according to the sub-criterion training and skills development.

O4	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	CHI	HI	HI	EI	VHI	HI	HI	EI	VHI	HI	HI
A2	CLI	EI	SLI	SLI	VLI	EI	LI	SLI	VLI	EI	SLI	EI
A3	LI	SMI	EI	SMI	LI	HI	EI	SMI	LI	SMI	EI	SMI
A4	LI	SMI	SLI	EI	LI	SMI	SLI	EI	LI	EI	SLI	EI
CR	0.071				0.071				0.045			

criterion weights only have a limited effect on results and there is not a noteworthy change in the ranking of alternatives.

Table 16
Evaluation of the alternatives according to the sub-criterion adoption of advanced analytical tools.

M1	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	CLI	LI	LI	EI	CLI	LI	LI	EI	CLI	LI	VLI
A2	CHI	EI	HI	SMI	CHI	EI	SMI	SMI	CHI	EI	HI	SMI
A3	HI	LI	EI	SLI	HI	SLI	EI	EI	HI	LI	EI	SLI
A4	HI	SLI	SMI	EI	HI	SLI	EI	EI	VHI	SLI	SMI	EI
CR	0.07				0.012				0.065			

Table 17
Evaluation of the alternatives according to the sub-criterion supply chain visibility.

M2	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	VLI	LI	SLI	EI	CLI	LI	LI	EI	CLI	LI	VLI
A2	VHI	EI	HI	HI	CHI	EI	HI	SMI	CHI	EI	HI	SMI
A3	HI	LI	EI	SMI	HI	LI	EI	SLI	HI	LI	EI	EI
A4	SMI	LI	SLI	EI	HI	SLI	SMI	EI	VHI	SLI	EI	EI
CR	0.091				0.07				0.051			

Table 18
Evaluation of the alternatives according to the sub-criterion financial approach.

M3	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	LI	VLI	CLI	EI	VLI	VLI	CLI	EI	LI	VLI	CLI
A2	HI	EI	EI	VLI	VHI	EI	EI	LI	HI	EI	SLI	VLI
A3	VHI	EI	EI	LI	VHI	EI	EI	LI	VHI	SMI	EI	SLI
A4	CHI	VHI	HI	EI	CHI	HI	HI	EI	CHI	VHI	SMI	EI
CR	0.096				0.09				0.079			

Table 19
Evaluation of the alternatives according to the sub-criterion customer orientation.

M4	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	VLI	LI	SLI	EI	VLI	VLI	SLI	EI	LI	SLI	SLI
A2	VHI	EI	EI	HI	VHI	EI	SMI	SMI	HI	EI	SMI	SMI
A3	HI	EI	EI	HI	VHI	SLI	EI	SMI	SMI	SLI	EI	EI
A4	SMI	LI	LI	EI	SMI	SLI	SLI	EI	SMI	SLI	EI	EI
CR	0.046				0.06				0.016			

5.4. *Comparative Analysis*

In this section, a comparative analysis is conducted to demonstrate the validity and verify the effectiveness of the proposed method. The results of our proposed IVFF-AHP method are compared with Buckley's ordinary fuzzy AHP and crisp-AHP. We used the scale of

Table 20
Evaluation of the alternatives according to the sub-criterion flexibility.

M5	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	VLI	LI	SMI	EI	CLI	VLI	SLI	EI	VLI	VLI	SLI
A2	VHI	EI	SMI	VHI	CHI	EI	EI	HI	VHI	EI	SMI	HI
A3	HI	SLI	EI	HI	VHI	EI	EI	SMI	VHI	SLI	EI	HI
A4	SLI	VLI	LI	EI	SMI	LI	SLI	EI	SMI	LI	LI	EI
CR	0.088				0.015				0.086			

Table 21
Evaluation of the alternatives according to the sub-criterion enhanced response management.

M6	E1				E2				E3			
	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EI	CLI	VLI	LI	EI	CLI	VLI	VLI	EI	VLI	LI	LI
A2	CHI	EI	SMI	HI	CHI	EI	SMI	SMI	VHI	EI	SMI	HI
A3	VHI	SLI	EI	SMI	VHI	SLI	EI	SMI	HI	SLI	EI	SMI
A4	HI	LI	SLI	EI	VHI	SLI	SLI	EI	HI	LI	SLI	EI
CR	0.065				0.093				0.093			

Table 22
Aggregated interval-valued fermatean fuzzy sets for main criteria.

Goal	DC	O	M
DC	([0.5, 0.5], [0.5, 0.5])	([0.632, 0.697], [0.315, 0.373])	([0.35, 0.4], [0.6, 0.65])
O	([0.29, 0.363], [0.639, 0.71])	([0.5, 0.5], [0.5, 0.5])	([0.126, 0.229], [0.773, 0.875])
M	([0.6, 0.65], [0.35, 0.4])	([0.765, 0.865], [0.149, 0.243])	([0.5, 0.5], [0.5, 0.5])

Table 23
Difference matrix for main criteria.

Goal	DC		O		M	
DC	0	0	0.2	0.307	−0.232	−0.152
O	−0.34	−0.21	0	0	−0.668	−0.449
M	0.152	0.232	0.434	0.645	0	0

Table 24
Interval multiplicative matrix.

Goal	DC		O		M	
DC	1	1	1.586	2.026	0.586	0.708
O	0.457	0.613	1	1	0.215	0.355
M	1.419	1.705	2.714	4.412	1	1

Table 25
Weights before normalization.

Goal	DC	O	M
DC	1	1.614	0.594
O	0.467	1	0.223
M	1.438	2.811	1

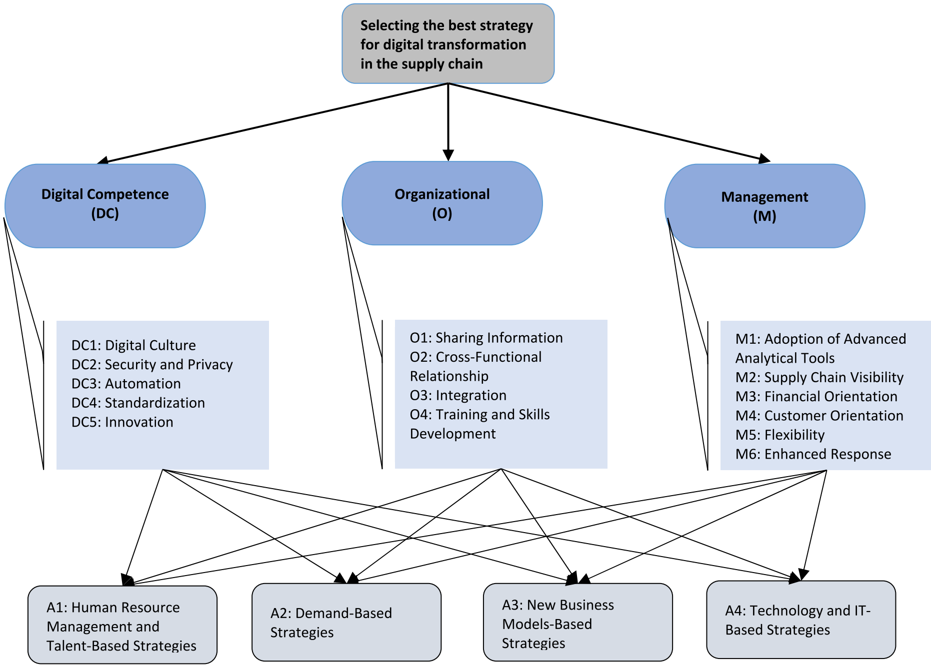

Fig. 5. Hierarchical structure of the problem.

Table 26
Priority and overall weights of criteria.

Main criteria	DC					O				M					
Weights	0.316					0.167				0.517					
Sub-criteria	DC1	DC2	DC3	DC4	DC5	O1	O2	O3	O4	M1	M2	M3	M4	M5	M6
Weights	0.32	0.1	0.21	0.08	0.29	0.33	0.15	0.39	0.13	0.27	0.22	0.05	0.26	0.08	0.11
Overall	0.10	0.03	0.07	0.02	0.09	0.055	0.025	0.066	0.021	0.14	0.11	0.03	0.14	0.04	0.06

Table 27
Priority weights of alternatives according to each criterion.

	DC1	DC2	DC3	DC4	DC5	O1	O2	O3	O4
A1	0.353	0.092	0.071	0.121	0.074	0.153	0.186	0.277	0.461
A2	0.121	0.155	0.224	0.197	0.310	0.455	0.398	0.375	0.126
A3	0.202	0.190	0.219	0.308	0.374	0.318	0.343	0.250	0.237
A4	0.324	0.564	0.487	0.375	0.242	0.074	0.073	0.099	0.176

	M1	M2	M3	M4	M5	M6
A1	0.080	0.091	0.069	0.127	0.109	0.079
A2	0.499	0.467	0.185	0.374	0.435	0.437
A3	0.191	0.220	0.238	0.296	0.319	0.274
A4	0.230	0.222	0.508	0.202	0.136	0.210

Table 28
Score values and ranking of alternatives.

Alternatives	A1	A2	A3	A4
Final scores	0.144	0.35	0.258	0.248
Rank	4	1	2	3

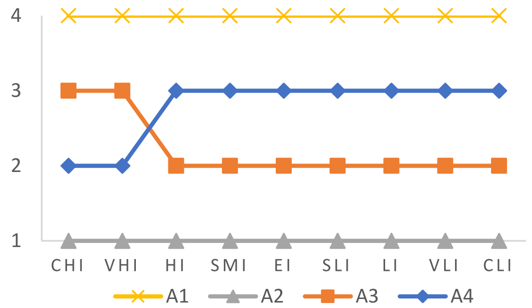

Fig. 6.a. Results of sensitivity analysis in *organizational* criterion with respect to *digital competence* criterion

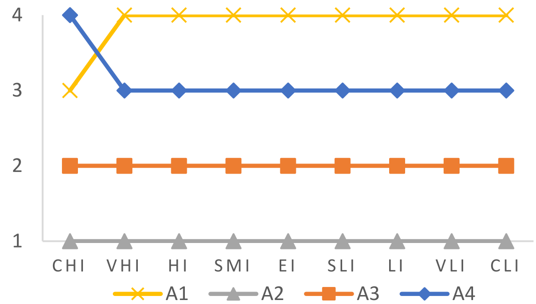

Fig. 6.b. Results of sensitivity analysis in *management* criterion with respect to *organizational* criterion

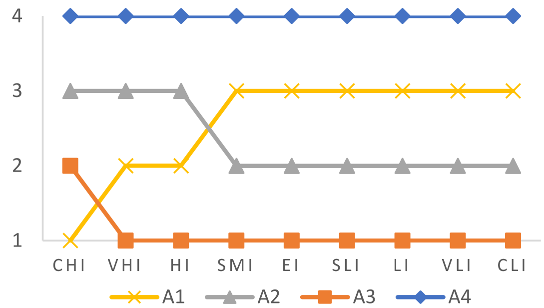

Fig. 6.c. Results of sensitivity analysis in *management* criterion with respect to *digital competence* criterion

Fig. 6. Results of sensitivity analysis in the main criteria weight.

Buckley's ordinary fuzzy AHP given in Table 29 and the scale of crisp-AHP given in Table 30 to assign the numerical values corresponding to experts' linguistic evaluations. Due to the space constraints, we only present the weights of criteria and ranking of alternatives obtained from ordinary fuzzy AHP and crisp-AHP methods. Table 31 and Table 32

Table 29
Buckley's ordinary fuzzy AHP scale.

Linguistic terms	Fuzzy numbers
Equally Importance	(1, 1, 3)
Slightly More Importance	(1, 3, 5)
High Importance	(3, 5, 7)
Very High Importance	(5, 7, 9)
Certainly High Importance	(7, 9, 9)

Table 30
Crisp-AHP scale.

Degree of importance	Scale	Reciprocal
Equally Importance	1	1
Moderate Importance	3	1/3
Strong Importance	5	1/5
Very Strong Importance	7	1/7
Extremely Importance	9	1/9

Table 31
Priority and overall weights of the criteria in the fuzzy AHP method.

Main criteria	DC					O				M					
Weights	0.203					0.08				0.717					
Sub-criteria	DC1	DC2	DC3	DC4	DC5	O1	O2	O3	O4	M1	M2	M3	M4	M5	M6
Weights	0.64	0.018	0.08	0.01	0.26	0.299	0.07	0.57	0.06	0.299	0.18	0.03	0.37	0.05	0.06
Overall	0.13	0.004	0.016	0.002	0.05	0.024	0.006	0.046	0.005	0.215	0.132	0.023	0.27	0.035	0.045

Table 32
Priority and overall weights of criteria in the crisp AHP method.

Main criteria	DC					O				M					
Weights	0.262					0.088				0.65					
Sub-criteria	DC1	DC2	DC3	DC4	DC5	O1	O2	O3	O4	M1	M2	M3	M4	M5	M6
Weights	0.43	0.06	0.18	0.04	0.285	0.33	0.09	0.51	0.07	0.284	0.216	0.03	0.33	0.054	0.08
Overall	0.11	0.02	0.047	0.01	0.075	0.03	0.008	0.045	0.006	0.185	0.14	0.02	0.217	0.035	0.054

demonstrate the priority and overall weights of criteria for each method, respectively. The final scores and ranking of alternatives for both methods are presented in Table 33 and Table 34, respectively.

When the results obtained with the proposed method are compared with the results obtained from both Buckley's ordinary fuzzy AHP and crisp-AHP methods, A2 is ranked as the best alternative in all methods (See Fig. 7). The rest of the ranking is followed by A3, A4, and finally A1 in Buckley's ordinary fuzzy AHP method while followed by A4, A3, and finally A1 in crisp-AHP method. Although the ranking of alternatives in Buckley's ordinary fuzzy AHP method gives the same results as our proposed method, the weights

Table 33
Results of the fuzzy AHP.

Alternatives	A1	A2	A3	A4
Final Scores	0.116	0.488	0.201	0.195
Rank	4	1	2	3

Table 34
Results of the crisp AHP.

Alternatives	A1	A2	A3	A4
Final Scores	0.109	0.43	0.23	0.232
Rank	4	1	3	2

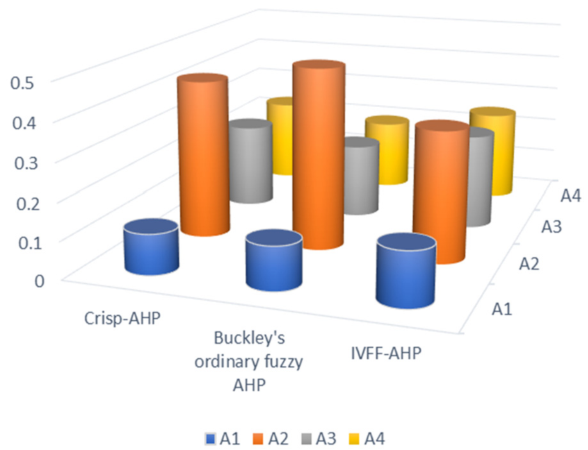

Fig. 7. Comparison results of the ranking of alternatives based on different evaluation environments.

of alternatives in the proposed method are different than other compared methods. The advantage of our proposed method, unlike other methods, is that the differences between the weights of the alternatives are more distinct. This difference is because FFSs present a larger domain for parameter assignment. Besides, the ranking differences that arise in the crisp- AHP method also come from the fuzzy evaluations of the proposed method.

6. Conclusion

To protect and sustain the existence of organizations with digitalization in today's competitive conditions, it has been inevitable to direct their traditional supply chains toward the digital supply chain transformation. With the digital transformation in the supply chain, information has the potential to reach the right place, the right time, and the right person. However, since the traditional supply chain has a complex structure, no enterprise has been able to initiate digital transformation in the supply chain. This situation has always been a challenging process for organizations by forcing organizations to remain in the initial stages of digital transformation. Therefore, there has been a need for a comprehensive framework to guide organizations.

There is a great lack in the literature on how digital transformation in the supply chain is realized, what the key success factors are, what kind of strategies should be developed and to which strategy priority should be given. This situation has revealed the need for an evaluation covering more than one criterion in a fuzzy environment. A fuzzy MCDM approach has been proposed to handle this evaluation process in this paper.

FFSs are quite suitable to handle uncertainty rather than other fuzzy set extensions by assigning the membership and non-membership degrees from a larger domain. IVFFSs address the problems in vague and uncertain environments more powerfully because they have the ability to express information more flexibly. Especially with the use of IVFFS in MCDM approaches, uncertainties are handled more strongly and thus the decision-making process can be managed more accurately with the proposed approach. In this study, IVFFSs have been introduced to better handle uncertainty and an IVFF-AHP method has been proposed. The developed method has been applied to identify the best strategy in the digital supply chain. The IVFF-AHP method has been successfully employed to determine the best strategy by making pairwise comparisons. In the study, we also developed a novel defuzzification method for IVFFSs.

This study has provided guidance and awareness about identifying critical success factors that are important for organizations to achieve the digital supply chain transformation, and to determine what kind of strategies they should first develop for a successful transformation. Besides, a systematic framework has been also developed to define the requirements of digital transformation in the supply chain. In this way, the main criteria and sub-criteria which are required for digital supply chain transformation have been determined and attention has been drawn to the criteria that organizations should first focus on.

Sensitivity analysis has shown that by changing the weights of the main criteria, the ranking of alternatives almost did not change, and this has proved that our decision-making process was quite robust and effective. Thus, the strength of the developed method has been demonstrated by the sensitivity analysis. A comparative analysis conducted together with Buckley's ordinary fuzzy AHP and crisp AHP showed that the developed method offers more consistent, reliable and informative results with more details about the uncertain decision-making environment.

For further research, the different IVFF-AHP and single-valued FFAHP methods such as triangular FFAHP or trapezoidal FFAHP can be developed. Alternatively, we suggest IVFF-AHP to be compared with other extensions of fuzzy sets such as neutrosophic AHP, interval-valued intuitionistic fuzzy AHP, interval-valued Pythagorean fuzzy AHP, or hesitant fuzzy AHP. Additionally, other multi-criteria decision-making methods such as TOPSIS or VIKOR can be extended to their IVFFSs extensions.

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