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IVPF-AHP integrated VIKOR methodology in supplier selection of three-dimensional (3D) printers

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Abstract

Complex geometries, fine details, and various designs that are difficult to create using traditional methods can easily be turned into a tangible object with Three-Dimensional (3D) printers. 3D printers have advantages such as providing design flexibility, obtaining prototypes in the shortest possible time, allowing for personalization, and reducing waste through the use of advanced technology. These advantages emphasize the significance of 3D printers in a sustainable production model. The widespread usage of 3D printers leads to increased efficiency and cost reduction in production. When the literature is examined, it is observed that there are limited studies on the evaluation of supplier performances for company using 3D printers. The aim of this study is to address 3D printers, which are highly significant for sustainable production, and to reveal the criteria that companies utilizing these printers need to consider for determining their suppliers. As a result of the literature review and expert interviews, a model has been developed that gathers the criteria to be considered for supplier selection, which is an important cost factor for companies involved in designing and producing 3D printers under five main and 18 sub-criteria. The importance weights of the criteria have been determined using the Interval Valued Pythagorean Fuzzy Analytic Hierarchy Process (IVPF-AHP) method, and the most suitable supplier among alternative suppliers has been selected using the Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method. Finally, the supplier scores have been statistically analyzed to show the validation of the results of the proposed method. According to the results, it has been concluded that for company using 3D printers, quality and technical service criteria are more important in the supplier selection. Additionally, cost of the material/equipment, product price and easy maintenance criteria also play a critical role in the supplier selection of 3D printer.

1. Introduction

Additive manufacturing (AM) is the process of transforming a digitally designed model into a physical object by building it layer by layer. AM is used worldwide in various sectors due to its contribution to the advancement of production technology, enabling process automation and real-time evaluation of data. AM offers many advantages compared to traditional manufacturing techniques, such as unlimited design freedom, decentralized manufacturing, on-demand manufacturing, quality improvement, and the ability to produce small-volume products [1]. These advantages highlight the significance of AM technology for creating a sustainable production model that minimizes adverse environmental effects, preserves energy and natural resources, and aims to produce rational products. AM which focuses on innovation and creativity, should take its place in production processes as part of a comprehensive sustainability plan [2]. Some of the commonly used AM processes in the fabrication process are stereolithography (SL), selective laser sintering (SLS), fused deposition modelling (FDM), 3D printing (3DP), laminated object manufacturing (LOM), polyjet printing (PP), electron beam melting (EBM), and laser engineered net shaping (LENS) The key advantage of adapting 3D printing technologies to traditional manufacturing processes is the ability to create complex, customized, and high-precision models [3]. 3D printers work in a similar way to traditional printers, but they use powder that gradually transforms into an image on a layer-by-layer basis. The use of smart materials and layer-by-layer addition of materials reduces raw material waste. This also leads to an increase in efficiency. 3D printers utilize three-dimensional Computer Aided Design (3D CAD) software to create each layer of the object [4]. The workflow diagram for the 3D printing process is shown in Figure 1.

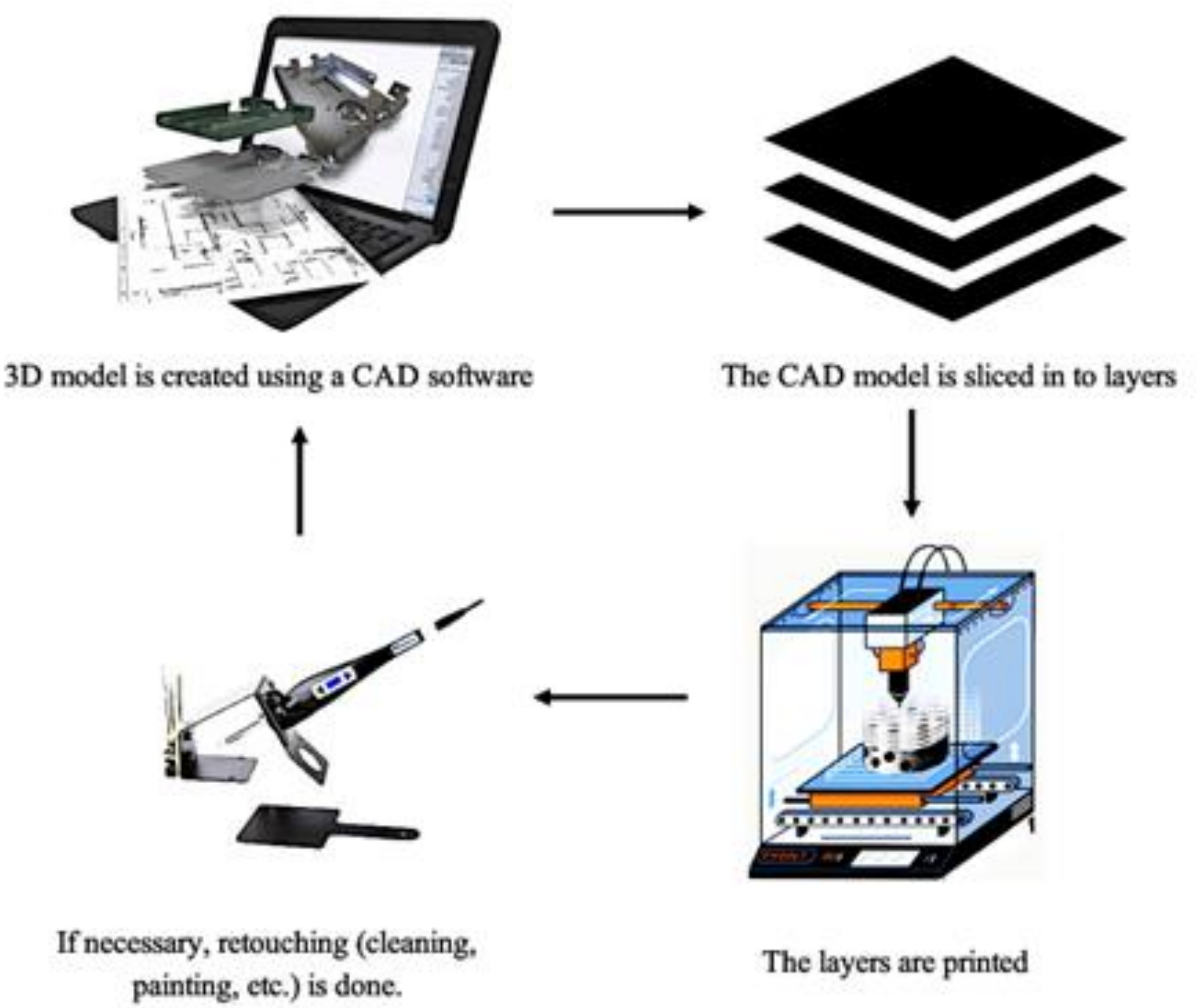

Figure 1. The workflow diagram of the 3D printing process [5].

Today, many 3D printers are produced to cater to different sectors. Such importance of 3D printers, which has the potential to meet the high-quality printing of all different sectors, makes the studies in this field valuable. The widespread use of 3D printers with high technology has led to the creation of many brands. Finding the most suitable supplier among these brands is critical for companies. Choosing the right supplier for the company will reduce the company's purchasing costs while increasing customer satisfaction and its competitive performance against its rivals in the market. For this reason, it is of great importance for the sector to determine the criteria that should be taken into account when choosing their own supplier among the suppliers of the companies that supply 3D printers.

In the competitive environment that develops in parallel with the developing technology in the business world, businesses offer their products and services by using their resources effectively in order to always be ahead of their competitors in the sector and to continue their existence for a long time. Choosing the most suitable supplier with minimum cost, in the fastest time and at the right time provides benefits in terms of increasing its profitability in line with increasing its competitive power [6].

Multi-Criteria Decision Making (MCDM) methods are divided into two categories: Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). The MADM method is referred to as discrete MCDM, while MODM is called continuous MCDM. The goal of MADM methods is to model decision processes based on criteria, maximizing the utility that decision-makers will obtain at the end of the process. MADM methods are designed to determine the best alternative, classify alternatives into a few categories, and/or rank alternatives according to subjective preference order. There are many methods suggested in the literature for this purpose. Table 1 provides commonly used MADM methods in the literature [7].

Table 1. The most commonly used MADM methods in the literature [7].

MADM Methods	Abbreviation	References
Entropy Method	Entropy	Shannon [8]
Simple Additive Weighting	SAW	Churchman and Ackoff [9]
Multi Attribute Utility Theory	MAUT	Fishburn [10]
Elimination et choice Translating Reality	ELECTRE	Benayoun et al. [11]
Multi-Attribute Value Theory	MAVT	Fishburn [12]
Weighted Product Method	WPM	Miller and Starr [13]
Decision Making Trial and Evaluation Laboratory	DEMATEL	Fontela and Gabus [14]
Simple Multi-Attribute Rating Technique	SMART	Edward [15]
Analytic Hierarchy Process	AHP	Saaty [16]
Technique for Order Preference by Similarity to Ideal Solution	TOPSIS	Hwang and Yoon [17]
Preference Ranking Organization Methods for Enrichment Evaluations	PROMETHEE	Brans et al. [18-19]
Measuring Attractiveness by a Categorical Based Evaluation Technique	MACBETH	Bana e Costa and Vansnick [20]
Complex Proportional Assessment Mth.	COPRAS	Kaklauskas et. al [21]
Analytic Network Process	ANP	Saaty [22]
Gray Relation Analysis	GRA	Deng [23]
Vise Kriterijumska Optimizacija I Kompromisno Resenje	VIKOR	Opricovic and Tzeng [24]
Multi-objective Optimization by Ratio Analysis	MOORA	Brauers and Zavadskas [25]
Multiple Objective Optimization on the Basis of Ratio Analysis	MULTIMOORA	Brauers and Zavadskas [26]
Additive Ratio Assessment	ARAS	Zavadskas and Turskis [27]
Weighted Aggregated Sum Product Assessment	WASPAS	Zavadskas et al., [28]
Evaluation Based on Distance from Average Solution	EDAS	Ghorabaee [29]
Best-Worst Method	BWM	Rezaei [30]

Several studies have effectively addressed a range of decision-making problems using the MCDM methods. For instance, Menekse et. al. [31] presented an integrated MCDM approach using PFSs to assess AM alternatives in the automotive industry. Özgüner and Özgüner [2] analyzed the impact of AM technology on sustainable production using the DEMATEL method. According to the results, AM technology has been revealed to have a significant impact on sustainable production with contributions such as the development of sustainable solutions, ensuring green production, promoting the production of innovative products, and preventing excessive resource use. Büyüközkan and Göçer [32] utilized the CODAS method under Pythagorean fuzzy in selection of the right 3D printing technology. Sahoo and Goswami [33] examined current studies by reviewing the literature on selecting environmentally friendly suppliers. Amiri et. al. [34] employed BWM method for sustainable supplier selection in the supply chain. Więckowski et. al. [35] evaluated battery suppliers using fuzzy MCDM methods in a fuzzy environment, discussing the importance of transportation cost, delivery time, and warranty periods. El-Morsy [36] conducted a stock portfolio analysis by defining the risky return rate, portfolio risk amount, and expected return rates with PFNs. Yazdani et. al. [37] established a sustainable supplier evaluation framework using NSs. Stević et. al. [38] developed a novel measurement and ranking of alternatives for sustainable supplier selection in the healthcare sector using the COMpromise Solution (MARCOS) method. Su et. al. [39] utilized Grey and DEMATEL methods to ensure the development of the hierarchical structure of sustainable supply chain management and to reveal the relationship among the critical criteria and a specific supplier. Nagarajan et. al [40] employed NSs in the selection of the best 3D printer.

In this study, Interval-Valued Pythagorean Fuzzy Analytical Hierarchy Process (IVPF-AHP) and VIseKriterijumsa Optimizacija I Kompromisno Resenje (VIKOR) methods are used in an integrated way. Information can sometimes be ambiguous due to various restrictions. If the information is not precise and clear, it is not possible for the decision maker to choose with exact numbers [41]. Pythagorean fuzzy numbers (PFNs), one of the new fuzzy set extensions, play an important role in defining information according to traditional fuzzy numbers in cases where the information is incomplete, ambiguous, and uncertain. In the definition of PFNs, the inclusion of a non-membership function, in addition to the membership function, allows for a better representation of expert opinions. The sum of the membership and non-membership functions can be greater than 1, but the sum of their squares cannot exceed 1. This also provides experts with the flexibility of defining, thereby minimizing uncertainty. PFNs are easy to implement in real life than other new fuzzy set extensions. PFNs with interval values are a new and effective decision-making tool. Due to these advantages, IVPF-AHP method is used to find the significance weights of the criteria in the proposed approach. The Analytic Hierarchy Process (AHP) method has been also applied to demonstrate the validity of the proposed model. The criteria weights obtained as a result of the IVPF-AHP and the AHP methods have been analyzed for the proposed model in SPSS software. The results obtained by statistical analysis confirm that the proposed model produced meaningful results.

In the VIKOR method, linear normalization is used, while the TOPSIS method employs vector normalization. The VIKOR method addresses the proximity to the ideal solution using an aggregation function, while the TOPSIS method is defined with two reference points. The TOPSIS method does not take into account the relative importance of distances to these reference points. In the PROMETHEE method, the results are based on the maximum group benefit. In the VIKOR method, it combines maximum group benefit with minimum individual regret. ELECTRE and VIKOR methods are based on similar principles [42]. Additionally, the VIKOR method provides operational ease compared to the ELECTRE method. That is why the VIKOR method has been preferred. The VIKOR method is based on the principle of determining the most suitable option based on existing criteria and ranking the options according to their performance. Experts were asked to score between 0 and 100 when comparing suppliers, as it would be much more difficult to compare five alternative suppliers by each criterion using linguistic expressions. Criteria weights obtained from the IVPF-AHP method have been transferred to the VIKOR method and experts were asked to evaluate five alternative suppliers based on the criteria. The results obtained according to the evaluations of the experts have been examined. The supplier scores obtained by IVPF-AHP and AHP methods are analyzed by the Paired Sample t-Test. As a result, there are no statistically meaningful differences between the two methods.

In Section 2, the literature review about determining the criteria to be considered for the selection of the 3D printer supplier of a business is included, the decision-making model created is shown. In Section 3, IVPF-AHP and VIKOR methods used in the study are explained and the previous studies are presented. In Section 4, the implementation made in the study is included and Section 5 contains the statistical analysis results used in the comparison of methods. In Section 6, evaluations are made about the data obtained as a result of the implementation and suggestions are made for the future studies.

2. Evaluation criteria of 3D printer supplier selection

In this study, the supplier selection problem of 3D printers is studied. For this problem, the main and sub-criteria are searched by literature review and the most appropriate ones are determined by consulting with the experts. The experts are determined by considering their experiences the supplier selection problem. These criteria and their brief literature review can be seen in Table 2.

Table 2. Literature review for the supplier selection criteria of 3D printers.

Main Criteria	Sub-criteria	Sources
Cost (C)		[43-46]
	Product price (C_1)	[46-50]
	Cost of the material/equipment (C_2)	[45,46], [49-51]
	Energy consumption cost of 3D printers (C_3)	[1, 4], [52-53]
Quality (Q)		[54-58]
	The compatibility of materials such as filament and nozzle (Q_1)	[4,31,44], [47-49], [54,59,60]
	Customer satisfaction (Q_2)	[45], [55-57], [61,62]
	Different type of 3D printers (Q_3)	[47,58,63]
Accessibility to Technology (A)		[4, 47,48,61,62]
	Geometric complexity (A_1)	[44,47,49]
	Extruders (A_2)	[4,46,50,61]
	Layer thickness (A_3)	[44,46], [48-50], [61]
	Waste disposal (A_4)	[1,4,47,58]
	Build speed (A_5)	[31,44], [46-50], [54]
Logistics Support (L)		[62,64,65]
	Delivery lead time/On-time delivery (L_1)	[47,62,64,66]
	Delivery reliability/Perfect delivery (L_2)	[65,67,68]
Technical Service (T)		[1,4,61,62]
	Ease of assembly (T_1)	[55,61,62]
	Interface installation (T_2)	[1,4,61,69]
	Spare part (T_3)	[62,70,71]
	Easy maintenance (T_4)	[1,55,61,62]

In this study, the supplier selection problem of 3D printers is considered and classified five different main criteria as Cost (C), Quality (Q), Accessibility to Technology (A), Logistics Support (L) and Technical Service (T) through literature review and expert interviews. Cost (C) is one of the main criteria for selecting the right supplier. Due to the use of new technology and their limited availability in the market, the prices of 3D printers were quite high. The widespread adoption of 3D printers and the increase in product variety have led to a decrease in the selling prices. However, whether the suppliers can provide the proper service that meets the business needs should be considered, as well as the price [72]. The cost criterion has three sub-criteria; Product Price (C_1), Cost of the material/equipment (C_2) and Energy consumption cost of 3D printers (C_3). Quality (Q) is the second main criterion. In order for enterprises to maintain their dominance in the sector, they must produce both affordable and quality products. Quality criterion consists of four sub-criteria; The compatibility of materials such as filament and nozzle (Q_1), Customer satisfaction (Q_2) and Different type of 3D printers (Q_3). The compatibility of materials such as filament and nozzle (Q_1), Filament is one of the essential materials used in the 3D printing process. The quality and properties of the filament directly impact the quality and success of 3D printing. The nozzle directly affects the level of detail and precision in the 3D printing process. The proper selection of the nozzle is crucial for achieving high-quality prints. Customer satisfaction (Q_2), if the product meets customer requirements, and the customer is satisfied with the service provided, this leads to customer satisfaction. The understanding the needs and expectations of customers and planning how services can be delivered within this framework is so important. Different type of 3D printers (Q_3), it is very significant to find product options in different types and capacities according to the specifications of the customer in order to find the product that the customer desires. The Accessibility to Technology (A) is the third main criterion. 2D printers perform the process of printing existing objects' letters or visuals, while 3D printers enable the physical touch of objects. In this way, 3D printers have been designed using innovative technology [73]. The accessibility to technology criterion consists of five sub-criteria; Geometric complexity (A_1), Extruders (A_2), Layer thickness (A_3), Waste disposal (A_4) and Build speed (A_5). These criteria are crucial for 3D printers to operate at the desired performance level. Logistics Support (L) is the fourth main criterion. No matter how quality the product is or how well it is promoted, if the consumer has difficulty in finding that product, the desire for that product will decrease over time and the tendency towards alternatives will begin. The logistics support criterion has two sub-criteria; Delivery lead time/On-time delivery (L_1) and Delivery reliability/Perfect delivery (L_2). Delivery lead time/On-time delivery (L_1), the delay in this period also delays the delivery to the customer. The Delivery reliability/Perfect delivery (L_2) criterion is very important as it is a disadvantage for the company if the product is missing or damaged when delivering the product. The Technical Service (T) is the final main criterion. It is very important for after-sales service that the product is installed or assembled and running after purchases. The technical support criterion consists of four sub-criteria; Ease of assembly (T_1), Interface installation (T_2), Spare part (T_3) and Easy maintenance (T_4). Ease of assembly (T_1) by evaluating both the conditions at the installation site and all factors with which product can proceed more easily and quickly. The interaction between users and 3D printers produced with advanced technology will be enhanced thanks to a comprehensible interface installation (T_2), causing increased user satisfaction. It is significant to be able to detect and supply the required spare parts as soon as possible. Therefore, the Spare part (T_3) criterion plays an important role. There are different assembly types depending on the 3D printer models. With technological developments, devices are constantly being renewed. The precision of 3D printers produced with advanced technology necessitates careful attention to maintenance. Therefore, the importance of the technical team's knowledge in ensuring ease of maintenance (T_4) is significant.

3. Methods

The fuzzy set theory (FST) introduced to literature by Zadeh [74]. The FST is used in situations where information is uncertain, vague, and incomplete. The Fuzzy Sets (FSs) have a single membership function. Sometimes, a decision maker may not exactly give a decision about a subject. Therefore, intuitionistic fuzzy sets (IFSs) that contain both membership and non-membership functions are developed by Atanassov [75]. Unlike the IFSs, the sum of membership and non-membership degrees cannot exceed 1. Pythagorean fuzzy sets (PFSs) developed by Yager [76]. The PFSs also have membership and non-membership functions but sum of their square cannot be greater than 1. These extensions have enabled the more flexible and detailed representation of uncertainty in various decision-making processes. Figure 2 presents the FSs and its extensions chronologically.

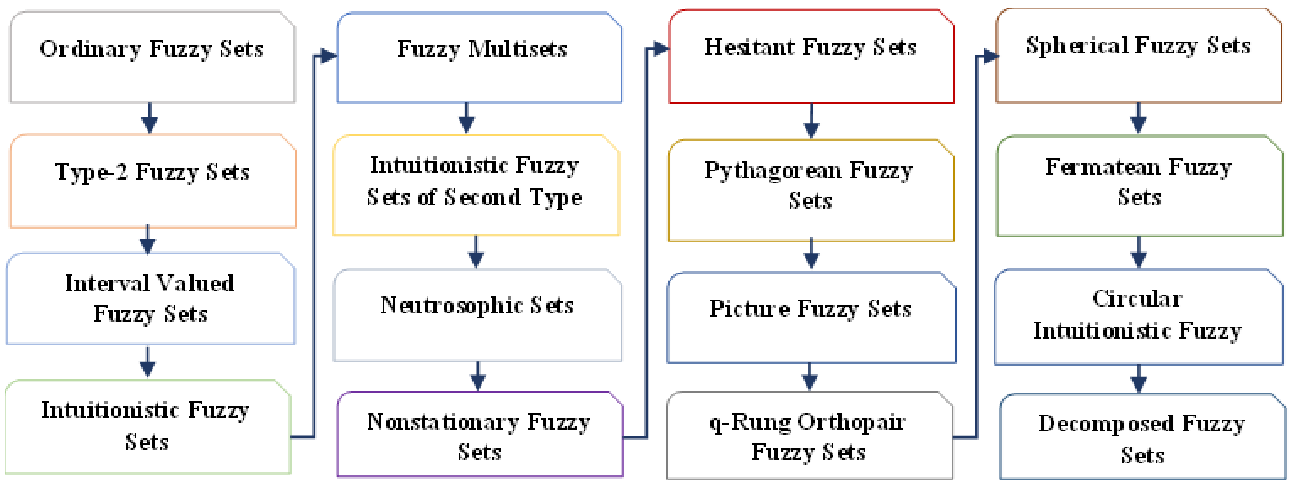

Figure 2. Fuzzy sets and its extensions [77].

PFSs are more flexible than other the FSs. Because of these advantages, PFSs are preferred in literature studies. AHP is used to determine the relative importance of activities in the MCDM problems. This method is based on pair-wise comparison of criteria or alternatives. Due to its popularity in decision-making problems, AHP has been expanded with new fuzzy set extensions to allow decision-makers to express uncertainty more effectively and in more detail in their linguistic evaluations [77]. F-AHP is extended of AHP method. It developed by Laarhoven and Pedrycz [78]. The details of the F-AHP method are not given owing to page count restriction, but the related reference is provided for readers in more detail about the method. PFSs integrated into the AHP method are implemented in situations where experts may not exactly decide and not fully reflect the thinking style of the experts.

Studies with PF-AHP method are summarized below: Karaşan et al. [79] used PF-AHP method for the selection of the most suitable clean energy technology. Otay and Jalley [80] evaluated wind energy farms in Türkiye using the PF-AHP method. İlkbahar et al. [81] examined renewable energy alternatives using Pythagorean Fuzzy WASPAS method. Mete [82] assessed occupational risks in pipeline construction by integrating PFSs into FMEA-based AHP-MOORA approach. Öz et al. [83] conducted a risk assessment for the cleaning and rating process of the natural gas pipeline project and used the PFSs based TOPSIS method to prioritize hazards. Bolturk and Kahraman [84] applied the Pythagorean fuzzy extension of CODAS method to select natural gas technology. Mete et al. [85] developed a decision support system based on Pythagorean fuzzy VIKOR method for occupational risk assessment of natural gas pipeline construction. Wood [86] made their supplier selection for oil industry facilities using flexible entropy weight and Intuitionistic fuzzy TOPSIS method. Yildiz et al. [87] determine best location for automated teller machine (ATM) via PF-AHP integrated Pythagorean fuzzy TOPSIS methodology. Coşkun et al. [88] have measured the marketing performance of an enterprise in the clothing industry using IVPF-AHP and interval-valued TOPSIS methods. Erdoğan et al. [89] measured the performance of retail companies by using Pythagorean Fuzzy TODIM methodology based on IVPF-AHP method.

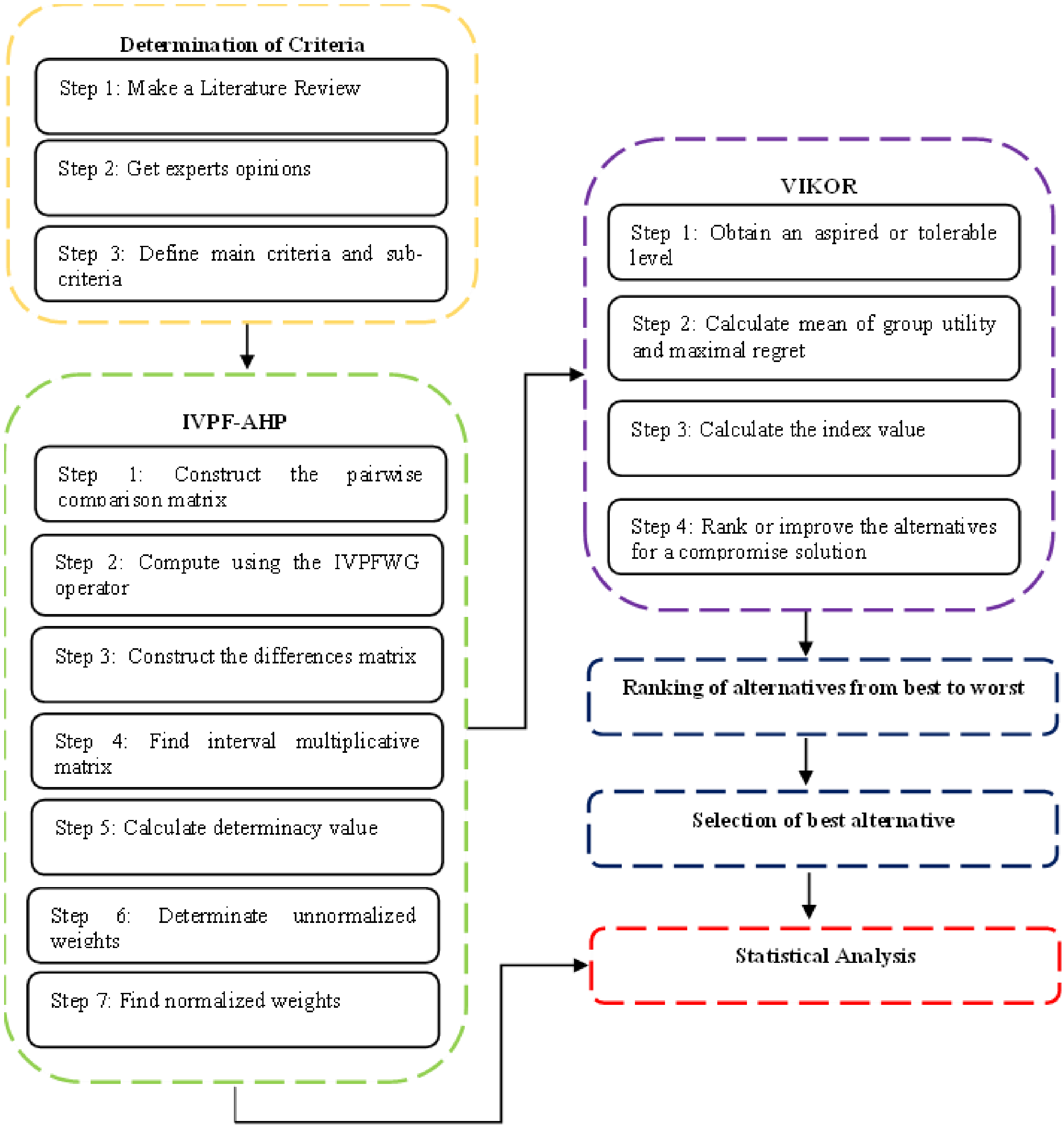

Figure 3. The proposed methodology.

When the literature is examined, it is observed that there are a limited number of studies with PFSs, which are new fuzzy sets extensions, neutrosophic sets (NSs) and hesitant fuzzy sets (HFSs) in the supplier selection of 3D printers. For this reason, interval-valued Pythagorean fuzzy sets (IVPFSs) have been used to find the importance weights of the criteria in the selection of a 3D printer supplier. IVPFSs, a new MDCM approach, expresses the uncertainty according to the degrees of membership and non-membership defined by flexible interval values. The VIKOR method has been used to compare alternative 3D printer brands. Finally, statistical analyses have been applied for the validation of the results of the proposed method in the study. The proposed methodology in the study is shown in Figure 3.

3.1. Interval-valued Pythagorean Analytic Hierarchy Process (IVPF-AHP)

3.1.1. Definitions of PFSs

In the decision-making process, decision-makers make their own evaluations for each of the alternatives. Some factors affecting decision-makers in an uncertain environment cause decision makers to be unable to make decisions with exact values. PFSs are applied to deal with these uncertainties. In PFSs, the membership and non-membership basic functions express uncertainty better. It helps to model the incomplete and subjective statements of decision makers in the best way [88].

The PFSs can be expressed as follows [90-94]:

Definition 1. Let X be a fixed set. A Pythagorean fuzzy set $\tilde{P}$ is defined as shown in Equation 1:

$$\tilde{P} \cong \{\langle x, \mu_{\tilde{P}}(x), v_{\tilde{P}}(x)\rangle; x \in X\} \tag{1}$$

A where $\mu_{\tilde{P}}(x): X \mapsto [0,1]$ defines the degree of membership and $v_{\tilde{P}}(x): X \mapsto [0,1]$ defines the degree of non-membership of the element $x \in X$ to $\tilde{P}$, respectively. Equation (2) is satisfied:

$$0 \leq \mu_{\tilde{P}}(x)^2 + v_{\tilde{P}}(x)^2 \leq 1; x \in X \tag{2}$$

The degree of hesitancy condition is as shown in Equation 3:

$$\pi_{\tilde{P}}(x) = \sqrt{1 - \mu_{\tilde{P}}(x)^2 - v_{\tilde{P}}(x)^2} \tag{3}$$

Definition 2. Let $\tilde{A} = \langle \mu_1, v_1 \rangle$ and $\tilde{B} = \langle \mu_2, v_2 \rangle$ be two Pythagorean Fuzzy Numbers (PFNs) and $\lambda > 0$. Then, the arithmetic operations of PFNs are as shown in Equation 4-7:

$$\tilde{A} \oplus \tilde{B} = \left(\sqrt{\mu_1^2 + \mu_2^2 - \mu_1^2\mu_2^2}, v_1 v_2\right) \tag{4}$$

$$\tilde{A} \otimes \tilde{B} = \left(\mu_1^2\mu_2^2, \sqrt{v_1^2 + v_2^2 - v_1^2 v_2^2}\right) \tag{5}$$

$$\lambda\tilde{A} = \left(\sqrt{1 - (1 - {\mu_1}^2)^\lambda}, {v_1}^\lambda\right) \tag{6}$$

$$\tilde{A}^\lambda = \left({\mu_1}^\lambda, \sqrt{1 - (1 - {v_1}^2)^\lambda}\right) \tag{7}$$

Definition 3. Let Int ([0,1]) denote the set of all closed subintervals of [0,1], and X be a universe of discourse. An IVPFS $\tilde{P}$ in X is given by Equation 8.

$$\tilde{P} = \{\langle x, \mu_{\tilde{P}}(x), v_{\tilde{P}}(x)\rangle; x \in X\} \tag{8}$$

where the functions $\mu_{\tilde{P}}(x): X \mapsto Int([0,1])$ $(x \in X \mapsto \mu_{\tilde{P}}(x) \subseteq [0,1])$ and $v_{\tilde{P}}(x): X \mapsto Int([0,1])$ $(x \in X \mapsto v_{\tilde{P}}(x) \subseteq [0,1])$ denote the membership degree and non-membership degree of the element $x \in X$ to the set $\tilde{P}$, respectively, and for every $x \in X$, $0 \leq \left\{\sup\left(\mu_{\tilde{P}}(x)\right)^2 + \left(v_{\tilde{P}}(x)\right)^2\right\} \leq 1$. Also, for each $x \in X$, $\mu_{\tilde{P}}(x)$ and $v_{\tilde{P}}(x)$ are closed intervals and their lower and upper bounds are denoted by $\mu_{\tilde{P}}^L(x), \mu_{\tilde{P}}^U(x)$, $v_{\tilde{P}}^L(x)$, $v_{\tilde{P}}^U(x)$, respectively. Therefore, $\tilde{P}$ can also be expressed in another style as shown in Equation 9:

$$\tilde{P} = \left\{\langle x, \left[\mu_{\tilde{P}}^L(x), \mu_{\tilde{P}}^U(x)\right], \left[v_{\tilde{P}}^L(x), v_{\tilde{P}}^U(x)\right]\rangle ; x \in X\right\} \tag{9}$$

The degree of hesitancy condition is as shown in Equation 10:

$$\pi_{\tilde{P}}(x) = \sqrt{1 - \mu_{\tilde{P}}^U(x)^2 - v_{\tilde{P}}^U(x)^2}, \sqrt{1 - \mu_{\tilde{P}}^L(x)^2 - v_{\tilde{P}}^L(x)^2} \tag{10}$$

Definition 4. Let $\widetilde{A_i}$, $i = (1,2, \ldots, n)$ be a collection of IVPFNs. Then, the Interval-Valued Pythagorean Fuzzy Weighted Power Geometric (IVPFWG) operator is as shown in Equation 11:

$$IVPFWG_w\left(\widetilde{A_1}, \widetilde{A_2}, \widetilde{A_3}, \ldots \widetilde{A_n}\right) = \left(\begin{matrix}\left[\prod_{i=1}^{n}(\mu_{Ai}^L)^{w_i}, \prod_{i=1}^{n}(\mu_{Ai}^U)^{w_i}\right], \\ \left[\begin{matrix}\sqrt{1 - \prod_{i=1}^{n}(1 - (v_{Ai}^L)^2)^{w_i}}, \\ \sqrt{1 - \prod_{i=1}^{n}(1 - (v_{Ai}^U)^2)^{w_i}}\end{matrix}\right]\end{matrix}\right) \tag{11}$$

where $w = (w_1, w_2, \dots, w_n)^T$ is the weighted vector of $\widetilde{A}_i$, $i = (1,2,\dots,n)$ with $w_i \geq 0$ and $\sum_{i=1}^{n} w_i = 1$.

3.1.2. The Steps of IVPF-AHP

The steps of the IVPF-AHP method can be explained as follows:

Step 1: Construct the compromised pairwise comparison matrix $R_{(r_{ik})mxm}$ with respect to experts' opinions according to Table 3.

Step 2: Construct the differences matrix $D = (d_{ik})_{mxm}$ between lower and upper values of membership and non-membership functions by using Equation (12-13).

$$d_{ik_L} = \mu^2{}_{ik_L} - v^2{}_{ik_U} \quad (12)$$

$$d_{ik_U} = \mu^2{}_{ik_U} - v^2{}_{ik_L} \quad (13)$$

Step 3: Find the interval multiplicative matrix $S = (s_{ik})_{mxm}$ by using Equation (14-15).

$$s_{ik_L} = \sqrt{1000^{d_L}} \quad (14)$$

$$s_{ik_U} = \sqrt{1000^{d_U}} \quad (15)$$

Step 4: Calculate the determinacy value $\tau = (\tau_{ik})_{mxm}$ by using Equation (16).

$$\tau_{ik} = 1 - \left(\mu^2{}_{ik_U} - \mu^2{}_{ik_L}\right) - \left(v^2{}_{ik_U} - v^2{}_{ik_L}\right) \quad (16)$$

Step 5: Determinate unnormalized weights $T = (t_{ik})_{mxm}$ by using Equation (17).

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2}\right)\tau_{ik} \quad (17)$$

Step 6: Find the normalized priority weights w_i by using Equation (18).

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2}\right)\tau_{ik} \quad (18)$$

Table 3. Weighing scale for the IVPF-AHP method.

Linguistic Terms	IVPFNNs			
	μ_L	μ_U	v_L	v_U
Certainly Low Importance (CLI)	0.00	0.00	0.90	1.00
Very Low Importance (VLI)	0.10	0.20	0.80	0.9
Low Importance (LI)	0.20	0.35	0.65	0.8
Below Average Importance (BAI)	0.35	0.45	0.55	0.65
Average Importance (AI)	0.45	0.55	0.45	0.55
Above Average Importance (AAI)	0.55	0.65	0.35	0.45
High Importance (HI)	0.65	0.80	0.20	0.35
Very High Importance (VHI)	0.80	0.90	0.10	0.20
Certainly High Importance (CHI)	0.90	1.00	0.00	0.00
Exactly Equal (EE)	0.1965	0.1965	0.1965	0.1965

3.2. VIKOR

The VIseKriterijumsa Optimizacija I Kompromisno Resenje (VIKOR) method was first developed by Opricovic and Tzeng [95] and for multi-criteria optimization of systems with complex structures. The VIKOR method helps to select the best alternative by using a multi-criteria ranking index to rank alternatives under a set of criteria. Development of the VIKOR method started with Equation (19) form of Lp-metric [96]:

$$L_i^p = \left\{\left[\sum_{j=1}^{n} w_j\left(\left|f_j^* - f_{ij}\right|\right) / \left(f_j^* - f_j^-\right)\right]^p\right\}^{1/p} \quad (19)$$

where, 1 ≤ p ≤ ∞; i = 1, 2, …, m.

Within the VIKOR method $L_i^{p=1} (as\ S_i)$ and $L_i^{p=\infty} (as\ R_i)$ are used to formulate ranking measure. The solution obtained by S_i is with a maximum group utility ("majority" rule), and the solution obtained by min R_i is with a minimum individual regret of the "opponent".

The steps of the ranking algorithm VIKOR can be explained as follows:

Step 1: Calculate the best f_j^* values and the worst f_j^* values of all criterion functions *j = 1, 2, …, n*. Assume that j^{th} function denotes benefits (Equation 20-21):

$$f_j^* = \max_i f_{ij} \quad (20)$$

$$f_j^- = \min_i f_{ij} \quad (21)$$

Step 2: Compute the values S_i and R_i. S_i is the synthesized gap for all criteria and R_i is the maximal gap in *i* criterion for prior improvement (Equation 22-23).

$$S_i = \sum_{j=1}^{n} w_j\left(\left|f_j^* - f_{ij}\right|\right) / \left(f_j^* - f_j^-\right) \quad (22)$$

$$R_i = \max_j\left(\left|f_j^* - f_{ij}\right|\right) / \left(f_j^* - f_j^-\right) \quad (23)$$

Step 3: Calculate the values Q_i. (Equation 24).

$$Q_i = v\frac{(S_i - S^*)}{(S^- - S^*)} + (1 - v)\frac{(R_i - R^*)}{(R^- - R^*)} \quad (24)$$

where, $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$ and v is introduced as the weight for the strategy of "maximum group utility", $(1 - v)$ is the weight of the individual regret of the "opponent".

Step 4: Sort the alternatives by the value of S_i, R_i ve Q_i in descending order. Propose the alternative $A^{(1)}$ as a compromise solution which is arranged by the measure minQ_i if the two conditions are satisfied:

Condition 1: Acceptable advantage (Equation 25)*:*

$$Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(m-1) \qquad (25)$$

where, m refers to the number of alternatives and $A^{(2)}$ is the second position among the alternatives ranked by Q_i.

Condition 2: Acceptable stability in decision making: Alternative $A^{(1)}$ must also be the best ranked by S_i or/and R_i.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

– Alternatives $A^{(1)}$ and $A^{(2)}$ if only condition 2 is not satisfied, or
– Alternatives $A^{(1)}, A^{(2)}, \ldots, A^{(M)}$ if condition 1 not satisfied; $A^{(M)}$ is determined by the relation $Q(A^{(M)}) - Q(A^{(1)}) < D(Q)$ for maximum M (the positions of these alternatives are close).

4. Real case application

With the widespread use of 3D printer in many sectors, the number of 3D printer suppliers has increased. It is crucial for businesses to find the most suitable supplier among these supplier companies. For this reason, it is of great importance for the sector to determine the criteria that should be taken into account when selecting their own supplier among the enterprises supplying 3D printer to the company. The integrated IVPF-AHP and VIKOR methods have been used in the study.

The necessary literature review is made for the criteria to be used in the selection of 3D printer supplier, and the criteria are determined in line with the interviews made with three expert teams with sufficient knowledge in the field. The criteria weights obtained using IVPF-AHP have been verified by the AHP method. Finally, the supplier scores obtained from the criterion weights of the two methods have been analyzed and their validity has been confirmed. The hierarchical structure of the application is shown in Figure 4.

In line with the evaluations of the experts, the 3D printers are separated according to their brands and the five preferred 3D printer brands are determined by the expert team. The identified brands are compared and ranked according to their performance levels. Criterion weights is found using the IVPF-AHP method. Criteria weights is transferred to the VIKOR method, and five alternative suppliers are evaluated with the VIKOR method. After that, the statistical analysis is done by Pearson Correlation Coefficient and Paired Simple t Test in SPSS software.

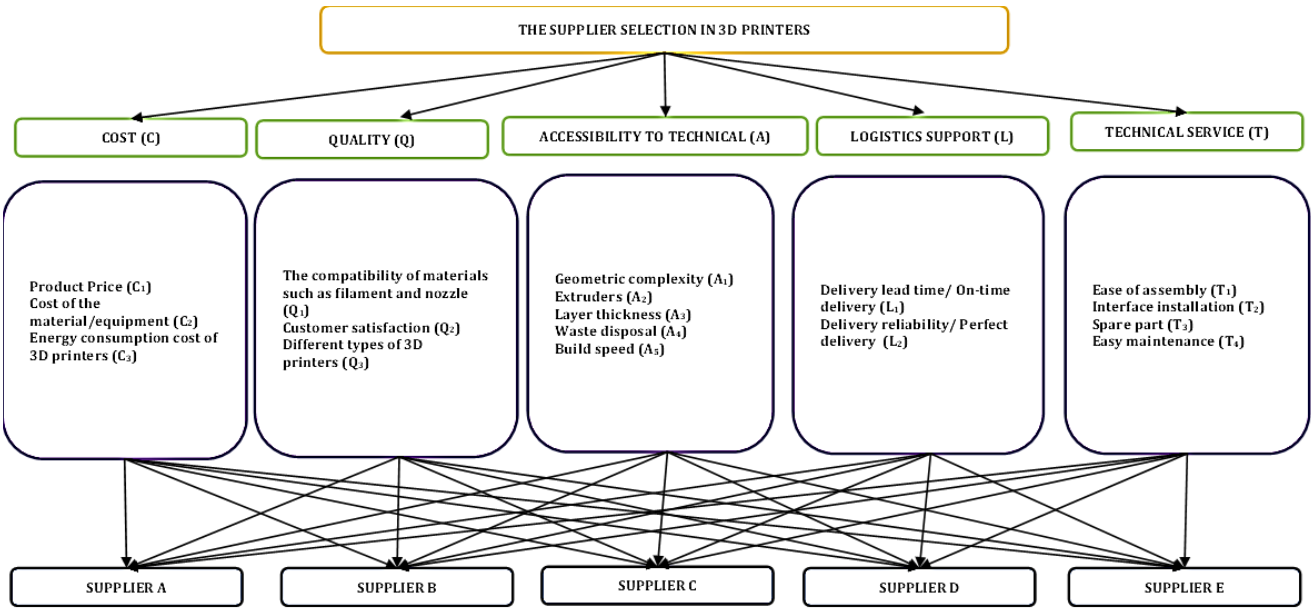

Figure 4. The hierarchical structure of the application

Experts were asked to evaluate the degree of influence of the criteria on each other with fuzzy linguistic expressions shown in Table 3. The impact assessment among the criteria by one of the experts is shown in Table 4. Linguistic expressions are translated into IVPFNs. PFNs with interval values corresponding to the linguistic evaluation of one of the experts are shown in Table 5. The consistency rates of each expert's evaluation matrix are calculated, and it is concluded that it is below 0.1. Criterion weights of the experts have determined as equally based on their years of experience in their field. Similarly, all evaluations made by the rest of the experts are translated into IVPFNs. IVPFNs are made into a single matrix using IVPFWG. The paired comparison matrix for the main criteria is shown in Table 6. The difference matrix shown in Table 7 is obtained by using the pairwise comparison matrix, Equation (12) and Equation (13). The interval multiplicative matrix shown in Table 8 is obtained by using the difference matrix, Equation (14) and Equation (15). Using Equation (16), certainty values are shown in Table 9. Unnormalized weight matrix is derived with certainty values. With the help of Equation (18), normalized priority weights are calculated and shown in Table 11.

According to the criterion weights obtained from the IVPF-AHP shown in Table 11, it is seen that the most important criterion to be considered in the selection of suppliers among the 3D printer brands in the sector is Quality. Supplier enterprises should focus on Quality and Technical Service criteria to increase their 3D printer sales.

Table 4. The evaluation values of one of the experts in terms of the effect between the main criteria.

	C	Q	A	L	T
C	EE	LI	LI	HI	AI
Q	HI	EE	EE	HI	EE
A	HI	EE	EE	AI	EE
L	LI	LI	AI	EE	LI
T	AI	EE	EE	HI	EE

Table 5. Corresponding IVPFNs for linguistic evaluation (CR = 0.041).

	C				Q				A				L				T			
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
C	0.1965	0.1965	0.1965	0.1965	0.10	0.20	0.80	0.90	0.10	0.20	0.80	0.90	0.35	0.45	0.55	0.65	0.20	0.35	0.65	0.80
Q	0.8	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.80	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965
A	0.8	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.65	0.80	0.20	0.35	0.1965	0.1965	0.1965	0.1965
L	0.55	0.65	0.35	0.45	0.10	0.20	0.80	0.90	0.20	0.35	0.65	0.80	0.1965	0.1965	0.1965	0.1965	0.10	0.20	0.80	0.90
T	0.65	0.80	0.20	0.35	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.80	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965

Table 6. Pairwise comparison matrix of main criteria.

	C				Q				A				L				T			
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
C	0.20	0.20	0.60	0.60	0.15	0.26	0.91	0.96	0.22	0.29	0.80	0.88	0.43	0.55	0.69	0.81	0.24	0.38	0.90	0.96
Q	0.71	0.81	0.71	0.77	0.20	0.20	0.60	0.60	0.47	0.52	0.49	0.62	0.66	0.78	0.61	0.73	0.36	0.41	0.82	0.87
A	0.38	0.43	0.82	0.87	0.16	0.24	0.94	0.98	0.20	0.20	0.60	0.60	0.50	0.62	0.83	0.88	0.16	0.20	0.93	0.97
L	0.39	0.53	0.88	0.94	0.19	0.32	0.92	0.97	0.34	0.47	0.79	0.87	0.20	0.20	0.60	0.60	0.13	0.20	0.95	0.98
T	0.62	0.75	0.62	0.74	0.28	0.36	0.77	0.84	0.31	0.33	0.49	0.60	0.50	0.54	0.48	0.60	0.20	0.20	0.60	0.60

Table 7. Differences matrix of the main criteria.

	C		Q		A		L		T	
	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}
C	-0.32	-0.32	-0.89	-0.76	-0.72	-0.56	-0.47	-0.19	-0.86	-0.67
Q	-0.10	0.15	-0.32	-0.32	-0.16	0.04	-0.11	0.23	-0.64	-0.51
A	-0.61	-0.49	-0.93	-0.83	-0.32	-0.32	-0.53	-0.31	-0.91	-0.83
L	-0.73	-0.49	-0.90	-0.74	-0.64	-0.41	-0.32	-0.32	-0.95	-0.86
T	-0.18	0.18	-0.63	-0.46	-0.26	-0.13	-0.11	0.07	-0.32	-0.32

Table 8. Interval multiplicative matrix of main criteria.

	C		Q		A		L		T	
	S_{ikL}	S_{ikU}	S_{ikL}	S_{ikU}	S_{ikL}	S_{ikU}	S_{ikL}	S_{ikU}	S_{ikL}	S_{ikU}
C	0.33	0.33	0.05	0.07	0.08	0.14	0.20	0.53	0.05	0.10
Q	0.71	1.69	0.33	0.33	0.58	1.13	0.69	2.22	0.11	0.17
A	0.12	0.18	0.04	0.06	0.33	0.33	0.16	0.34	0.04	0.06
L	0.08	0.18	0.05	0.08	0.11	0.24	0.33	0.33	0.04	0.05
T	0.55	1.85	0.11	0.20	0.41	0.64	0.69	1.25	0.33	0.33

Table 9. The determinacy values of main criteria.

	C	Q	A	L	T
	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}
C	1.00	0.87	0.84	0.72	0.81
Q	0.75	1.00	0.80	0.66	0.87
A	0.88	0.90	1.00	0.78	0.92
L	0.76	0.85	0.77	1.00	0.92
T	0.65	0.83	0.87	0.83	1.00

Table 10. The unnormalized weights of the main criteria.

	C	Q	A	L	T
	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}
C	0.33	0.05	0.10	0.26	0.06
Q	0.90	0.33	0.69	0.97	0.12
A	0.13	0.04	0.33	0.20	0.05
L	0.10	0.05	0.14	0.33	0.04
T	0.78	0.13	0.45	0.80	0.33

Table 11. The normalized weights for each criterion.

Main Criteria	w (%)
Cost	10.41
Quality	38.92
Accessibility to Technology	09.78
Logistic Support	08.58
Technical Service	32.31

When examined in terms of supplier selection in the additive manufacturing, it is observed that especially Cost and Accessibility to Technology criteria come well after Quality and Technical Service criteria.

For this reason, these two criteria are among the determining factors in supplier selection. The steps applied in the IVPF-AHP method for the main criteria are also applied for the sub-criteria, and the significance weights of the sub-criteria are shown in tables.

When the sub-criteria are examined, it is seen in Table 12 that the cost of the material/equipment and product price are more important than the energy consumption cost of 3D printers in the selection of suppliers based on cost criteria. When Table 13 is analyzed based on quality criteria, it is concluded that the compatibility of materials such as filament and nozzle is of critical importance when compared with other criteria. When Table 14 is examined, based on accessibility to technology criteria, it is noticed that build speed and layer thickness are very important compared to other criteria. When Table 15 is analyzed on the basis of logistic support criteria, it stands out that the delivery reliability and perfect delivery of products is more important than other criteria when choosing a supplier. The delivery of the product in non-damaged condition and ensuring the delivery reliability of the product enhances the customer's trust in the supplier, as it prevents adventure the security of the product. When Table 16 is assessed on the basis of technical service, it is seen that the easy maintenance is more important than the interface installation criteria. The reason for this is the production of 3D printers with new and different technologies, which results in higher costs. This study revealed that 3D printer suppliers should especially strengthen their Quality and Technical Service infrastructure to increase their customers. When the literature is also reviewed, it is seen that the results of this study are in line with the literature.

The criteria weights used in the VIKOR method come from the IVPF-AHP method, as the methods are used in an integrated manner. In the IVPF-AHP method, experts are asked to evaluate the criteria according to their importance with the fuzzy linguistic expressions shown in Table 3. For this reason, the criteria weights used in VIKOR are fuzzy. No deterministic action has been taken in criterion weights. Experts are asked to score between 0-100 when comparing suppliers, as it would be much more difficult to compare five different 3D printer suppliers, which we define as A, B, C, D, E, according to each criterion with linguistic expressions. For this reason, the VIKOR method has been preferred. The scores and the maximum and minimum scores of each criterion are shown in Table 17 where 0 is very bad and 100 is very good. The results obtained by calculating the group benefit average and maximum regret average of each supplier are listed in Table 18.

Table 12. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of cost criterion.

	C1				C2				C3				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
C1	0.20	0.20	0.60	0.60	0.29	0.41	0.87	0.92	0.39	0.44	0.72	0.79	23,69
C2	0.58	0.70	0.72	0.80	0.20	0.20	0.60	0.60	0.62	0.75	0.62	0.74	58,15
C3	0.29	0.34	0.84	0.89	0.24	0.38	0.90	0.96	0.20	0.20	0.60	0.60	18,16

Table 13. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of quality criterion.

	Q1				Q2				Q3				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
Q1	0.20	0.20	0.60	0.60	0.31	0.33	0.49	0.60	0.44	0.49	0.51	0.63	50.14
Q2	0.16	0.20	0.93	0.97	0.20	0.20	0.60	0.60	0.28	0.29	0.61	0.63	26.38
Q3	0.19	0.26	0.94	0.97	0.24	0.26	0.65	0.68	0.20	0.20	0.60	0.60	23.48

Table 14. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of accessibility to technology criterion.

	A1				A2				A3				A4				A5				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
A1	0.20	0.20	0.60	0.60	0.24	0.26	0.82	0.87	0.24	0.31	0.85	0.91	0.47	0.63	0.87	0.93	0.16	0.24	0.94	0.98	10.88
A2	0.28	0.29	0.71	0.77	0.20	0.20	0.60	0.60	0.34	0.39	0.75	0.81	0.53	0.66	0.82	0.88	0.20	0.29	0.89	0.95	15.21
A3	0.41	0.47	0.71	0.78	0.34	0.39	0.83	0.88	0.20	0.20	0.60	0.60	0.49	0.54	0.59	0.61	0.24	0.31	0.88	0.94	22.53
A4	0.24	0.38	0.78	0.89	0.28	0.43	0.81	0.89	0.00	0.00	0.83	1.00	0.20	0.20	0.60	0.60	0.15	0.26	0.91	0.96	09.98
A5	0.47	0.52	0.49	0.62	0.44	0.50	0.60	0.72	0.41	0.47	0.62	0.73	0.71	0.81	0.71	0.77	0.20	0.20	0.60	0.60	41.40

Table 15. The pairwise comparison matrix of all the expert evaluations and the sub-criteria weights of logistic support criterion.

	L1				L2				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
L1	0.20	0.20	0.60	0.60	0.16	0.20	0.93	0.97	19.16
L2	0.31	0.33	0.49	0.60	0.20	0.20	0.60	0.60	80.84

Table 16. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of the technical service criterion.

	T1				T2				T3				T4				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
T1	0.20	0.20	0.60	0.60	0.62	0.72	0.72	0.79	0.22	0.29	0.80	0.88	0.16	0.24	0.91	0.96	20.71
T2	0.23	0.34	0.89	0.94	0.20	0.20	0.60	0.60	0.00	0.00	0.87	1.00	0.00	0.00	0.94	1.00	09.47
T3	0.38	0.43	0.82	0.87	0.59	0.71	0.82	0.87	0.20	0.20	0.60	0.60	0.22	0.29	0.93	0.97	16.36
T4	0.47	0.52	0.59	0.71	0.72	0.86	0.59	0.72	0.38	0.43	0.56	0.68	0.20	0.20	0.60	0.60	53.46

Table 17. Evaluation scores of 3D printer suppliers belonging to different brands according to the criteria.

	A	B	C	D	E	f_j^*	f_j^-
C1	22	24	60	62	37	62	22
C2	38	25	61	47	39	61	25
C3	77	40	20	25	12	77	12
Q1	72	44	14	18	18	72	14
Q2	81	49	29	20	32	81	20
Q3	76	43	28	56	33	76	28
A1	74	17	24	31	16	74	16
A2	62	39	35	15	13	62	13
A3	61	38	44	21	17	61	17
A4	69	41	29	24	23	69	23
A5	68	45	29	12	28	68	12
L1	65	12	39	63	27	65	12
L2	54	13	53	60	42	60	13
T1	77	20	50	17	14	77	14
T2	75	35	34	12	13	75	12
T3	69	38	18	56	45	69	18
T4	75	50	37	34	39	75	34

Table 18. Ranking of 3D printer suppliers belonging to different brands according to the criteria weights obtained from the IVPF-AHP.

S_i	Rank	R_i	Rank	Q_i	Rank
0.072	A	0.039	A	0.000	A
0.660	B	0.105	B	0.608	B
0.732	D	0.182	D	0.902	D
0.734	C	0.183	E	0.945	C
0.816	E	0.195	C	0.962	E

By examining Condition 1 (acceptable advantage) and Condition 2 (an acceptable advantage in decision making) in the VIKOR method, according to Condition 1 and Condition 2, among the listed suppliers Qi, supplier A with the smallest value has been chosen due to its highest performance level.

5. Comparative analysis

A statistical analysis is important to prove the validity of the model in MCDM methods. For this, the results of the methods can be tested using various statistical analyses. SPSS is a statistical software package that allows the many different types of analysis, transformation, and forms of output of complex data. In addition to statistical analyses, it also provides various tools for data visualization, data manipulation, and reporting [97-98]. The relationship between the criteria weights obtained by MCDM methods can be analyzed using the correlation coefficient. The analysis of the results in determining the best alternative obtained from different criteria weights can be analyzed by the correlation coefficient or paired sample t-Test in the VIKOR method.

When Figure 5 is examined, both methods give similar results. However, decision-makers may not always have complete knowledge about a subject, and information is often uncertain in real-life problems. In such situations, the AHP method needs to be revised. The IVPF-AHP is more successful than the AHP method due to its flexibility in defining for decision-makers and its success in modeling uncertainty in real-life problems.

The correlation coefficient or r coefficient is a statistical tool used to measure the degree or strength of the relationship between two different variables. The correlation coefficient is considered to represent ≤ 0.35 weak correlations, 0.36 to 0.67 modest correlations, 0.68 to 1.00 high correlations and ≥ 0.90 very high correlations [99].

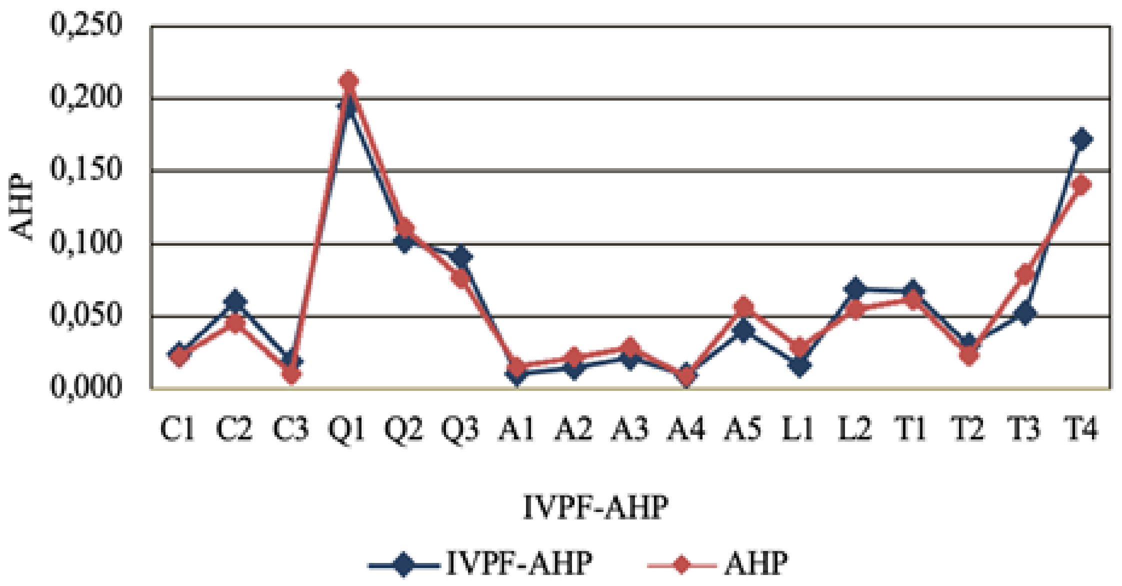

Figure 5. Comparison of the criteria weights obtained from the methods.

According to Figure 6, the correlation coefficient and test significance value of the methods are 0.9302 and 0.000, respectively. A very strong statistically positive correlation has been found between the criteria weights obtained from IVPF-AHP and the criteria weights obtained from AHP (P <.001).

The supplier scores determined using different methods in Table 19 is analyzed with a paired sample t-Test. It tests whether there is a significant difference between the two groups. The five supplier scores are analyzed by paired sample t-Test.

According to Table 20 and Table 21, 99% confidence level, test statistic and significance values are 1.633 and 0.178, respectively. As a result of the analysis, there are no statistically significant differences between the results of the two methods. The correlation coefficient according to the total scores of 3D printer suppliers with IVPF-AHP and AHP methods is 1.000. Thus, the proposed approach can be used for the 3D printer supplier selection.

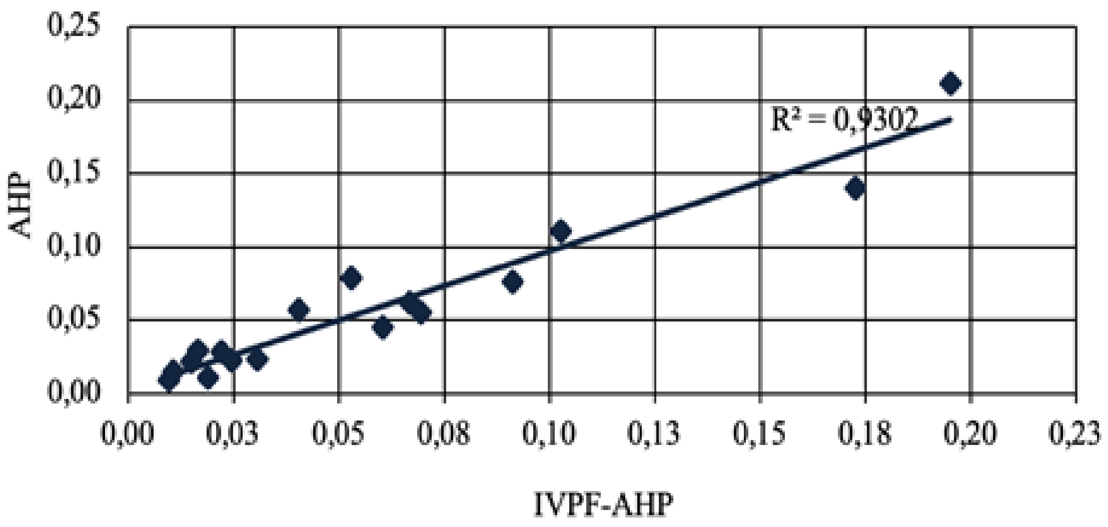

Figure 6. Correlation graph of the criteria weights obtained from the methods.

Table 19. Total scores of 3D printer suppliers according to the IVPF-AHP and the AHP methods.

		A	B	C	D	E
IVPF-AHP	C	04	03	06	05	03
	Q	29	17	08	11	10
	A	06	04	03	02	02
	L	05	01	04	05	03
	T	24	13	12	10	10
	Total	69	38	33	33	29
AHP	C	3	2	4	4	3
	Q	30	18	8	10	10
	A	9	5	4	2	3
	L	5	1	4	5	3
	T	23	12	11	11	10
	Total	69	38	32	32	29

Table 20. Analysis of the criteria weights of IVPF-AHP and AHP methods with paired sample t-Test in five suppliers.

	Paired Differences							
				99% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
IVPF-AHP & AHP	.40000	.54772	.24495	-.28009	1.08009	1.633	4	.178

Table 21. Correlation coefficient according to the total scores of 3D printer suppliers.

	Correlation Coefficient	Sig.
IVPF-AHP & AHP	1.000	.000

6. Conclusion

In the business world where competition is increasing day-by-day in parallel with the changing technological developments, companies must be superior to their competitors and more open to innovations to increase their profitability and maintain their continuity. At this point, the decision-making process constitutes the most important stage. When the developing technology, printers have also begun to evolve and change. This transformation has led to the emergence of many 3D printer brands.

Selection supplier for 3D printer has become crucial for businesses that want to choose their own supplier. In this study, the criteria to be considered to choose the best among the 3D printer suppliers are collected under five main criteria and 17 sub-criteria, and a model is created. The criteria determined are evaluated, and their opinions are received by a team of three experts who have a command in the field. The criteria weights are determined, and the result is assessed by listing the criteria according to their importance. This study revealed that supplier enterprises operating in the 3D printer should strengthen their quality and technical service infrastructures to increase their sales. It has been concluded that the criteria regarding the cost of the material/equipment, the compatibility of materials such as filament and nozzle, the ability of delivery reliability of products, easy maintenance are more important than other criteria. The suppliers are evaluated with the VIKOR method, and supplier A with the highest performance level is selected among the suppliers. According to the result of the statistical analysis, the proposed approach can be preferred for the 3D printer supplier selection.

It is seen that all enterprises the 3D printer can benefit from the results obtained from this study. In addition, it is clearly seen that the work done is valuable due to the importance of the 3D printer in today. 3D printers offer various advantages, including good fabrication speed, low material costs, and contributions to sustainable manufacturing. However, there are limitations in the potential to create large-scale models. Although mass production of identical parts is possible, challenges such as printing speed and cost can be obstacles. Additionally, issues like surface finish, moderate strength, and material availability can cause difficulties for suppliers. In future studies, these problems could be addressed with the integration of artificial intelligence technologies. The criteria created can be increased, more suppliers can be examined, and studies can be conducted with neutrosophic sets and hesitant fuzzy sets, which are the extension of new fuzzy sets and are more successful in defining uncertainty than traditional fuzzy sets. Furthermore, the effect of supplier selection on a supply chain can be investigated.

Conflicts of interest

The authors declare no conflicts of interest.

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