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Evaluation of 3D printers used in additive manufacturing by using interval type-2 fuzzy TOPSIS method

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Abstract

Recently, additive manufacturing technology, which is used in production and especially in prototyping, provides facilities to manufacturers in terms of speed and cost. 3D (three-dimensional) printer technologies used in additive manufacturing make itself felt in almost every sector. There are many functional 3D printers in the market and many criteria are considered in the purchase process. Because the selection of an incorrect printer can cause problems to manufacturers in terms of production and time. For this, multi-criteria decision-making methods can be used to select the suitable 3D printer. In this study, it is aimed to select the most suitable 3D printer that will buy for use in prototyping operations of a company operating in production sector. According to the defined criteria (max printing volume, layer resolution, price, positioning precision), the interval type-2 fuzzy TOPSIS method is used to evaluate the alternatives. At the end of the study, sensitivity analysis is performed, alternatives are evaluated, and finally the most suitable 3D printer is determined.

Keywords: Additive manufacturing; 3D printer; interval type-2 fuzzy TOPSIS.

1. Introduction

The production process is always in a movement and development with the development of technology. It is also important to follow technical and technological developments to optimize the organization costs. Simulation of critical details on the model, particularly in architectural design and R&D applications, is necessary to minimize errors in the final product. Situations that increase unpredictable costs during the process flow in mass production adversely affect the price of the final product. The rapid prototyping technology, which is developed because of proactive thinking and rapidly spreading, is increasingly being used due to its advantages for many sectors. At the end of the twentieth century, layered production emerged by the development of rapid prototyping machines, in other words, 3D printing technology has brought with it concepts related to the new generation production concept such as personalized production, low volume production and personal fabrication [1]. 3D printing technology is the process in which a 3-dimensional model can be readily available from any location or output in solid form. This resulting material output is also called layered production because two-dimensional (2D) layers are formed by overlapping layers [2, 6]. While defining 3D printing technology, words such as multiples production, 3D printing production, self-renewing production, instant production, additive manufacturing, production everywhere and digital production are used [7]. The widespread use of additive manufacturing technologies is the basis for the Industrial Revolution (4.0), as it is a new manufacturing method or a production system for the fourth industrial revolution [4]. Additive manufacturing is one of the modern (unconventional) manufacturing methods and is considered to be different from traditional processing techniques based on material extraction by cutting and drilling methods used in today's industry [2, 3, 6]. This is because, unlike conventional manufacturing methods, the part to be produced is based on the principle of three-dimensional parts manufacturing by replacing the raw material with the laser source or by adding them in layers in the case of flow, depending on the method, instead of chip breaking or mass forming. Productions carried out by this method are also referred to as three-dimensional printing, since digital design is transformed directly into three-dimensional parts [2, 8].

Although 3D printing technology has existed since 1986, it has been widely used in the market after 2010 [2]. Although it is still a very new technology and continues to be developed, it has already been used in industrial design, engineering, architecture, military,

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medical sector, biotechnology, fashion, food and many other fields [7, 9-11]. Dr. Charles Hull in 1984, a physics engineer, developed 3D printers used in 3D printing technology. After the development of this printer that has been printed by stereolithography method, it could not be used daily for many years. In 2006, Reprap and Fab@home project started to enter into daily use as a result of the production of open source, low cost 3D printers [12, 13]. In its simplest form, the 3D printer is a device that converts data stored in a computer environment to physical real objects. These printers can use many different technologies to perform production [3]. These machines are similar to CNC (Computer Numeric Control) systems as a design [14]. In this technique, the part is manufactured from a 3D model obtained by different methods such as drawing with computer aided design programs, reverse engineering and computed tomography. The 3D model is divided into several thin layers (sliced) and the manufacturing systems use this geometric data to fabricate each layer sequentially until the part is complete [4]. 3D printers were initially discovered to create three-dimensional objects, with the aim of performing the manufacture of complex parts in a single step using materials such as metals, ceramics and polymers [15, 16]. Nowadays, it is used to produce functional parts at the stage of obtaining prototypes, components and systems by creating a very large industrial area [10]. Printing in 3D printing technology is made using production techniques such as Melt Accumulation Modeling (MAM), Ink-jet, Sintering (SLS - Selective Laser Sintering, DLMS - Direct Laser Metal Sintering), Selective Laser Melting (SLM), Laminated Object Manufacturing (LOM). When considering the current development process and working logic of 3D printers, it is inevitable that these printers take their place in our daily lives and use this new technology in many areas [2]. Today, the list of materials that can be used as raw materials is changing day by day. So much so, that from the clothing sector to the food sector, the effect of 3D printers is provided by the raw materials used. In addition, the features of printers are effective in the development and diversification of these areas. Because each raw material does not give similar results. The use of printer suitable for raw materials is very important [17]. The advantages of 3D printers can be summarized as follows;

- Design can be easily transferred / shared due to digital data
- Changes and corrections can be made quickly
- Personalized products can be produced easily
- Efficient in terms of investment and production
- Relatively low initial investment cost
- Product price can be calculated before production
- Minimum waste from material
- Using convertible materials

3D printers have many parameters for efficient production. Important parameters from these parameters are listed below.

Layer thickness: It is the parameter that determines the precision in the Z-axes of the part. It is usually 0.25 mm and can be reduced to 0.1 mm. *Filling pattern*: This parameter determines the geometry in the inner fill layers of the piece. *Fill quantity*: One of the most important features of the 3D printer is the ability to produce without the need to fill the inside volume of the part. 100% solid production is possible if a robust and durable product is desired. 20% occupancy rate is sufficient if only for a visual production. *Speed and temperature:* The most critical parameters of the 3D printer. The temperature at which the nozzle will be heated and how fast it will move is determined by these parameters. It can usually differ depending on the material and the part geometry to be produced [3]. *Print speed:* The selected print speed directly affects the quality of 3D printing. Printing at very high print speeds reduces the quality and printing at very low print speeds will extend the printing time. One of the most important points in 3D printers is the *resolution*. Resolution can be given to various standards such as dots per inch (DPI), Z-layer thickness, and pixel size. In addition, there are many criteria such as surface quality, transparency, minimum detail, color element, thermal resistance, flexibility, production time, production costs, frequency of maintenance, calibration problem, continuity of part production quality, material options. For this reason, the process of buying a 3D printer is a decision-making process in which many criteria must be taken into account. Intuitive and mathematical methods can be used to solve problems such as these.

In this study, the interval type-2 fuzzy TOPSIS method, which is one of the multi-criteria decision making methods, is used to determine the most suitable 3D printer to be used in additive manufacturing. In the second section of the study, type-2 fuzzy TOPSIS method, which is used as a solution method, is mentioned briefly and algorithm steps are given. In the third section, the identified alternative 3D printers are evaluated. In the last section, the findings obtained from the study are included and evaluations are made.

2. Interval type-2 fuzzy TOPSIS method

Fuzzy TOPSIS method is one of the methods that are widely used in multi-criteria decision-making problems. Hwang and Yoon (1981) developed the method [18-20]. The basic definition of this method is to choose the shortest distance from the positive ideal solution and the alternative, which is the farthest distance from the negative ideal solution. There are many researches used this method in solving decision-making problems. However, the original fuzzy TOPSIS is not always appropriate to represent uncertainties due to the use of a type-1 fuzzy cluster. Therefore, Zadeh [21] have been proposed type-2 fuzzy sets (T2FS) to address uncertainties. However, because the T2FS proposed by Zadeh had very complex calculations, it was difficult to use in real-life applications. Therefore, Liang and Mendel [22] have developed the new concept of T2FS, which makes more calculations that are useful. T2FS is characterized by type-2 membership functions. The membership functions of the T2FS are three-dimensional and contain one-step of uncertainty. The highest and lowest fuzzy membership function in T2FS is obtained from the type-1 fuzzy membership function. The space between these two functions is a trace of the uncertainty used to characterize the type-2 fuzzy cluster [23]. To deal with the uncertainty, decision making with interval type-2 fuzzy sets (IT2FS) and linguistic variables have been shown to be more effective than traditional decision-making tools [24]. In their study, Chen and Lee [25] have developed the new type of fuzzy TOPSIS method, which is a new method for solving fuzzy multi-criteria decision-making problems, which extends the classical TOPSIS method and includes interval type-2 fuzzy sets. The interval type-2 fuzzy TOPSIS method provides more rational and more flexibility to calculate the weights and values of the criteria as it uses T2FS to solve fuzzy multi-criteria decision making problems [26]. Below is the steps of the interval type-2 fuzzy TOPSIS method.

Lee and Chen [26] presented the concept of ranking values of trapezoidal interval type-2 fuzzy sets. Let $\tilde{\tilde{A}}_i$ be an interval type-2 fuzzy set shown in Figure 1, where

$\tilde{\tilde{A}}_i = \left(\tilde{A}_i^U . \tilde{A}_i^{L,}\right) = ((a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U; H_1(\tilde{A}_i^U), H_2(\tilde{A}_i^L)))$.

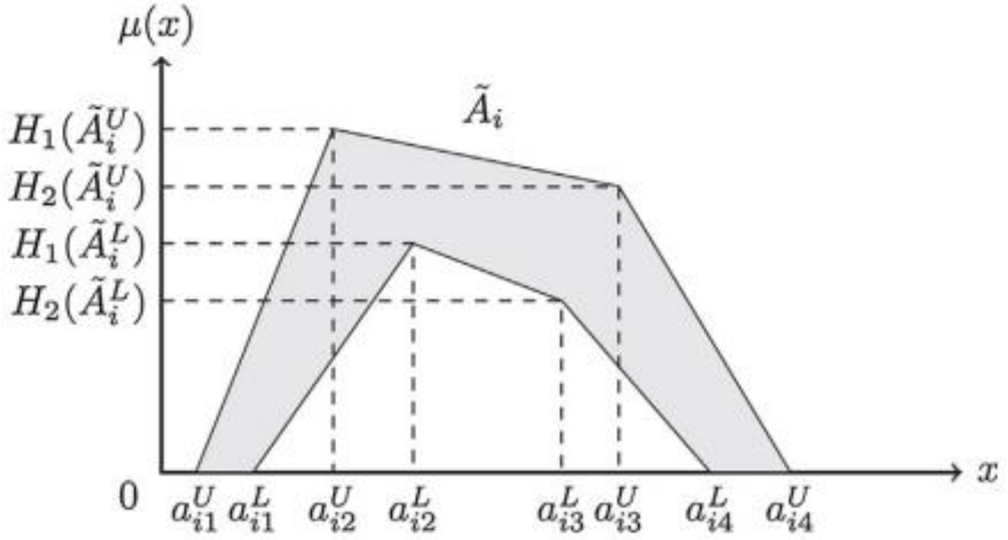

Figure 1. A trapezoidal interval type-2 fuzzy sets A [26]

The ranking value $Rank(\tilde{\tilde{A}}_i)$ of the trapezoidal interval type-2 fuzzy set $\tilde{\tilde{A}}_i$ is defined as follows [26]:

$$Rank(\overset{\approx}{A}_i) = M_1\left(\tilde{A}_i^U\right)+M_1\left(\tilde{A}_i^L\right)+M_2\left(\tilde{A}_i^U\right)+M_2\left(\tilde{A}_i^L\right)+ M_3\left(\tilde{A}_i^U\right)+M_3\left(\tilde{A}_i^L\right)-\frac{1}{4}\begin{pmatrix} S_1\left(\tilde{A}_i^U\right)+S_1\left(\tilde{A}_i^L\right)+ \\ S_2\left(\tilde{A}_i^U\right)+S_2\left(\tilde{A}_i^L\right)+ \\ S_3\left(\tilde{A}_i^U\right)+S_3\left(\tilde{A}_i^L\right)+ \\ S_4\left(\tilde{A}_i^U\right)+S_4\left(\tilde{A}_i^L\right) \end{pmatrix}+ H_1\left(\tilde{A}_i^U\right)+H_1\left(\tilde{A}_i^L\right)+H_2\left(\tilde{A}_i^U\right)+H_2\left(\tilde{A}_i^L\right) \quad (1)$$

where $M_p(\tilde{A}_i^j)$ denotes the average of the elements a_{ip}^j and $a_{i(p+1)}^j$,

$M_p(\tilde{A}_i^j) = (a_{ip}^j + a_{i(p+1)}^j)/2,\ 1 \le p \le 3,\ S_q(\tilde{A}_i^j)$ denotes the standard deviation of the elements a_{iq}^j and $a_{i(q+1)}^j$,

$$S_q(\tilde{A}_i^j) = \sqrt{\frac{1}{2}\sum\nolimits_q^{q+1}\left(a_{ik}^j - \frac{1}{2}\sum\nolimits_{k=q}^{q+1} a_{ik}^j\right)^2},$$

$1 \le q \le 3$, $S_4(\tilde{A}_i^j)$ denotes the standard deviation of the elements $a_{i1}^j, a_{i2}^j, a_{i3}^j, a_{i4}^j$,

$$S_4(\tilde{A}_i^j) = \sqrt{\frac{1}{4}\sum\nolimits_{k=1}^{4}\left(a_{ik}^j - \frac{1}{4}\sum\nolimits_{k=1}^{4} a_{ik}^j\right)^2},$$

$H_p(\tilde{A}_i^j)$ denotes the membership value of the element $a_{i(p+1)}^j$ in the trapezoidal membership function $\tilde{A}_i^j$, $1 \le p \le 2$, $j \in \{U, L\}$, and $1 \le i \le n$. In Eq. (1), the summation of

$$M_1\left(\tilde{A}_i^U\right), M_1\left(\tilde{A}_i^L\right), M_2\left(\tilde{A}_i^U\right), M_2\left(\tilde{A}_i^L\right), M_3\left(\tilde{A}_i^U\right), M_3\left(\tilde{A}_i^L\right), H_1\left(\tilde{A}_i^U\right), H_1\left(\tilde{A}_i^L\right), H_2\left(\tilde{A}_i^U\right)\ and\ H_2\left(\tilde{A}_i^L\right)$$

is called the basic ranking score, where we deduct the average of

$$S_1\left(\tilde{A}_i^U\right), S_1\left(\tilde{A}_i^L\right), S_2\left(\tilde{A}_i^U\right), S_2\left(\tilde{A}_i^L\right), S_3\left(\tilde{A}_i^U\right), S_3\left(\tilde{A}_i^L\right), S_4\left(\tilde{A}_i^U\right)\ and\ S_4\left(\tilde{A}_i^L\right)$$

from the basic ranking score to give the dispersive interval type-2 fuzzy set a penalty, where $1 \le i \le n$.

Assume that there is a set *X* of alternatives, where $X = \{x_1, x_2, \ldots, x_n\}$, and assume that there is a set *F* of attributes, where $F = \{f_1, f_2, \ldots, f_m\}$. Assume that there are *k* decision-makers $D_1, D_2, \ldots,$ and D_k. The set *F* of attributes can be divided into two sets F_1 and F_2, where F_1 denotes the set of benefit attributes, F_2 denotes the set of cost attributes, $F_1 \cap F_2 = \phi$, and $F_1 \cup F_2 = F$. The proposed method is now presented as follows:

Step 1: Construct the decision matrix Y_p of the *pth* decision-maker and construct the average decision matrix $\overline{Y}$, respectively, shown as follows:

$$Y_p = (\tilde{f}_{ij}^{\,p})_{mxn} = \begin{array}{c|cccc|} & x_1 & x_2 & \cdots & x_n \\ \hline f_1 & \overset{\approx}{f}{}_{11}^{p} & \overset{\approx}{f}{}_{12}^{p} & \cdots & \overset{\approx}{f}{}_{13}^{p} \\ f_2 & \overset{\approx}{f}{}_{21}^{p} & \overset{\approx}{f}{}_{22}^{p} & \cdots & \overset{\approx}{f}{}_{23}^{p} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ f_m & \overset{\approx}{f}{}_{31}^{p} & \overset{\approx}{f}{}_{m1}^{p} & \cdots & \overset{\approx}{f}{}_{mn}^{p} \end{array} \quad (2)$$

$$\overline{Y} = \left(\overset{\approx}{f}_{ij}\right)_{mxn}, \quad (3)$$

where, $(\overset{\approx}{f}_{ij}) = \left(\dfrac{\overset{\approx}{f}{}_{ij}^{1} \oplus \overset{\approx}{f}{}_{ij}^{2} \oplus \ldots . \oplus \overset{\approx}{f}{}_{ij}^{k}}{k}\right)$, $\overset{\approx}{f}_{ij}$ is an interval type-2 fuzzy set, $1 \le i \le m$, $1 \le j \le n$, $1 \le p \le k$, and k denotes the number of decision-makers.

Step 2: Construct the weighting matrix W_p of the attributes of the pth decision-maker and construct the average weighting matrix $\overline{W}$, respectively, shown as follows:

$$W_p = (\overset{\approx}{w}{}_i^p)_{1xm} = \left[\overset{\approx}{w}{}_1^p \quad \overset{\approx}{w}{}_2^p \quad \cdots \overset{\approx}{w}{}_m^p\right], \quad (4)$$

$$\overline{W} = (\overset{\approx}{w}_i)_{1xm}, \quad (5)$$

where $\overset{\approx}{w}_i = \left(\dfrac{\overset{\approx}{w}{}_i^1 \oplus \overset{\approx}{w}{}_i^2 \oplus .... \oplus \overset{\approx}{w}{}_i^k}{k} \right)$, $\overset{\approx}{w}_i$ is an interval type-2 fuzzy set, $1 \le i \le m,\ 1 \le p \le k,$ and k denotes the number of decision-makers. *Step 3:* Construct the weighted decision matrix $\overline{Y}_w$,

$$\overline{Y}_w = (\overset{\approx}{v}_{ij})_{mxn} = \begin{array}{c} \\ f_1 \\ f_2 \\ \vdots \\ f_m \end{array} \begin{array}{c} \begin{array}{cccc} x_1 & x_2 & \cdots & x_n \end{array} \\ \begin{bmatrix} \overset{\approx}{v}_{11} & \overset{\approx}{v}_{12} & \cdots & \overset{\approx}{v}_{13} \\ \overset{\approx}{v}_{21} & \overset{\approx}{v}_{22} & \cdots & \overset{\approx}{v}_{23} \\ \vdots & \vdots & \vdots & \vdots \\ \overset{\approx}{v}_{m1} & \overset{\approx}{v}_{m2} & \cdots & \overset{\approx}{v}_{mn} \end{bmatrix} \end{array}, \tag{6}$$

where $\overset{\approx}{v}_{ij} = \overset{\approx}{w}_i \otimes \overset{\approx}{f}_{ij}$, $\quad 1 \le i \le m$, and $1 \le j \le n$.

Step 4: Based on Eq. (1), calculate the ranking value $Rank\,(\overset{\approx}{v}_{ij})$ of the interval type-2 fuzzy set $\overset{\approx}{v}_{ij}$, where $1 \le j \le n$. Construct the ranking weighted decision matrix $\overline{Y}{}_w^*$,

$$\overline{Y}{}_w^* = \left(Rank(\overset{\approx}{v}_{11}) \right)_{mxn}, \tag{7}$$

where $1 \le i \le m$, and $1 \le j \le n$.

Step 5: Determine the positive ideal solution $x^+ = \left(v_1^+, v_2^+, \ldots\ldots v_m^+\right)$ and the negative-ideal solution $x^- = \left(v_1^-, v_2^-, \ldots\ldots v_m^-\right)$, where

$$v_i^+ = \begin{cases} \max\limits_{1 \le j \le n} \{rank(\overset{\approx}{v}_{ij})\}, & if \quad f_i \in F_1 \\ \min\limits_{1 \le j \le n} \{rank(\overset{\approx}{v}_{ij})\}, & if \quad f_i \in F_2 \end{cases} \tag{8}$$

and

$$v_i^- = \begin{cases} \min\limits_{1 \le j \le n} \{rank(\overset{\approx}{v}_{ij})\}, & if \quad f_i \in F_1 \\ \max\limits_{1 \le j \le n} \{rank(\overset{\approx}{v}_{ij})\}, & if \quad f_i \in F_2 \end{cases} \tag{9}$$

where F_1 denotes the set of benefit attributes, F_2 denotes the set of cost attributes, and $1 \le i \le m$

Step 6: Calculate the distance $d^+(x_j)$ between each alternative x_j and the positive ideal solution x^+, shown as follows:

$$d^+(x_j) = \sqrt{\sum_{i=1}^{m} (Rank\,(\overset{\approx}{v}_{ij}) - v_i^+)^2} \tag{10}$$

where $1 \le j \le n.$ Calculate the distance $d^-(x_j)$ between each alternative x_j and the negative-ideal solution x^-, shown as follows:

$$d^-(x_j) = \sqrt{\sum_{i=1}^{m} (Rank\,(\overset{\approx}{v}_{ij}) - v_i^+)^2} \tag{11}$$

where $1 \le j \le n.$

Step 7: Calculate the relative closeness index $C(x_j)$ of x_j with respect to the positive ideal solution x^+, shown as follows:

$$C(x_j) = \frac{d^-(x_j)}{d^-(x_j) + d^+(x_j)}, \tag{12}$$

where $1 \le j \le n.$

Step 8: Ranking the values of $C(x_j)$ in a descending sequence, where $1 \le j \le n.$ The larger the value of $C(x_j)$, the higher the preference of the alternative x_j, where $1 \le j \le n.$

3. Evaluation of 3D printers by using the interval type-2 fuzzy TOPSIS method

In this study, we aimed to selection the most suitable 3D printers for a company operating in the manufacturing sector in Turkey. For this aim, Interval type-2 Fuzzy TOPSIS method, which is one of the most criteria decision-making methods and which gives more accurate results than fuzzy TOPSIS method, is used. The criteria to be taken into consideration during the process of purchasing 3D printers are determined by literature review and alternatives for the 3D printer intended to be purchased are jointly determined by four people who will use the 3D printer. After this stage, a hierarchical selection model given in Figure 2 is created to select the most suitable 3D printer.

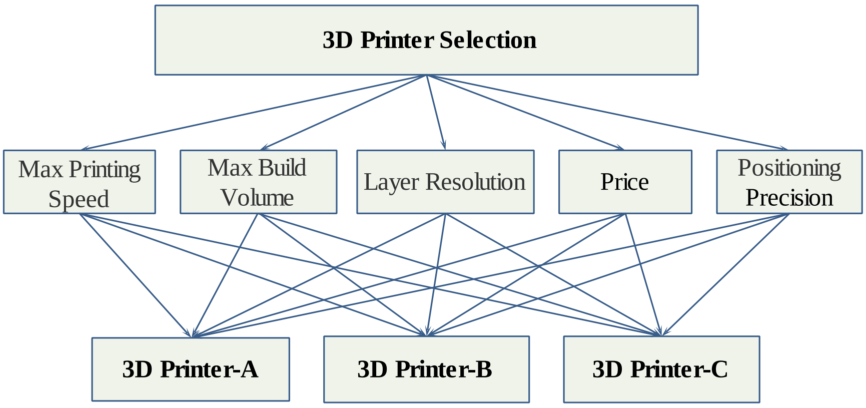

Figure 2. Hierarchical selection model for most suitable 3D printer selection.

Since the 3D printer to be purchased will be supplied as imported, the criteria data of alternative 3D printers have been determined from www.aliexpress.com and these values are given in Table 1.

Table 1. Criteria values for alternative 3D printers.

Alternatives 3D Printers	**Criteria**				
	Max. Printing Speed (mm/s)	Max. Build Volume (mm)	Layer Resolution (mm)	Price ($)	Positioning Precision (mm)
3D Printer-A	350	214x186x160	0.05-0.3	682	X,Y axis:0.0110 Z axis:0.0025
3D Printer-B	130	400x400x400	0.1-0.4	546	XY axis: 0.0125 Z axis: 0.0050
3D Printer-C	150	400x400x400	0.1-0.4	650	XY axis: 0.0120 Z axis: 0.004

After obtaining the criterion data, alternative printers for the selection of the most suitable 3D printer were evaluated according to the steps described above of the interval type-2 fuzzy TOPSIS method.

Step 1: The criteria values given in Table 1 were transformed into linguistic expressions in Table 2 by applying a specific method by four decision makers evaluating 3D printers and the decision matrix in Table 3 was created.

Table 2. Linguistic terms and interval type-2 fuzzy sets

Linguistic terms	**Interval type-2 fuzzy sets**
Very Low (VL)	((0, 0, 0, 0.1; 1, 1), (0, 0, 0, 0.05; 0.9, 0.9))
Low (L)	((0, 0.1, 0.1, 0.3; 1, 1), (0.05, 0.1, 0.1, 0.2; 0.9, 0.9))
Medium Low (ML)	((0.1, 0.3, 0.3, 0.5; 1, 1), (0.2, 0.3, 0.3, 0.4; 0.9, 0.9))
Medium (M)	((0.3, 0.5, 0.5, 0.7; 1, 1), (0.4, 0.5, 0.5, 0.6; 0.9, 0.9))
Medium High (MH)	((0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9))
High (H)	((0.7, 0.9, 0.9, 1; 1, 1), (0.8, 0.9, 0.9, 0.95; 0.9, 0.9))
Very High (VH)	((0.9, 1, 1, 1; 1, 1), (0.95, 1, 1, 1; 0.9, 0.9))

Table 3. Linguistic evaluation of alternative 3D printers and decision matrix

Criteria	**Alternatives 3D Printers**		
	3D Printer-A	3D Printer-B	3D Printer-C
Max Printing Speed	VH	L	ML
Max Build Volume	ML	MH	MH
Layer Resolution	MH	ML	ML
Price	MH	VH	H
Positioning Precision	VH	MH	H

After the decision matrix was formed, $\tilde{\tilde{f}}_{ij}$ values were obtained by eq.3 and fuzzy decision matrix in Table 4 was formed.

Table 4. Fuzzy decision matrix.

Criteria	**Alternatives 3D Printers**		
	3D Printer-A	3D Printer-B	3D Printer-C
Max Printing Speed	(0.9, 1, 1, 1; 1, 1), (0.95, 1, 1, 1; 0.9, 0.9)	(0, 0.1, 0.1, 0.3; 1, 1), (0.05, 0.1, 0.1, 0.2; 0.9, 0.9)	(0.1, 0.3, 0.3, 0.5; 1, 1), (0.2, 0.3, 0.3, 0.4; 0.9, 0.9)
Max Build Volume	(0.1, 0.3, 0.3, 0.5; 1, 1), (0.2, 0.3, 0.3, 0.4; 0.9, 0.9)	(0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)	(0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)
Layer Resolution	(0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)	(0.1, 0.3, 0.3, 0.5; 1, 1), (0.2, 0.3, 0.3, 0.4; 0.9, 0.9)	(0.1, 0.3, 0.3, 0.5; 1, 1), (0.2, 0.3, 0.3, 0.4; 0.9, 0.9)
Price	(0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)	(0.9, 1, 1, 1; 1, 1), (0.95, 1, 1, 1; 0.9, 0.9)	(0.7, 0.9, 0.9, 1; 1, 1), (0.8, 0.9, 0.9, 0.95; 0.9, 0.9)
Positioning Precision	(0.9, 1, 1, 1; 1, 1), (0.95, 1, 1, 1; 0.9, 0.9)	(0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)	(0.7, 0.9, 0.9, 1; 1, 1), (0.8, 0.9, 0.9, 0.95; 0.9, 0.9)

Step 2: With the common opinion of four decision makers, the criteria are evaluated and the weight matrix given in Table 5 is obtained.

Step 3: Then the weighted fuzzy decision matrix is obtained by using the eq.6 and given in Table 6.

Table 5. The linguistic evaluation of 3D printer purchasing criteria and the weight matrix

Criteria	**Linguistic terms**	**Interval type-2 fuzzy sets**
Max Printing Speed	MH	(0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)
Max Build Volume	H	(0.7, 0.9, 0.9, 1; 1, 1), (0.8, 0.9, 0.9, 0.95; 0.9, 0.9)
Layer Resolution	M	(0.3, 0.5, 0.5, 0.7; 1, 1), (0.4, 0.5, 0.5, 0.6; 0.9, 0.9)
Price	H	(0.7, 0.9, 0.9, 1; 1, 1), (0.8, 0.9, 0.9, 0.95; 0.9, 0.9)
Positioning Precision	M	(0.3, 0.5, 0.5, 0.7; 1, 1), (0.4, 0.5, 0.5, 0.6; 0.9, 0.9)

Table 6. Weighted fuzzy decision matrix.

Criteria	**Alternatives 3D Printers**		
	3D Printer-A	3D Printer-B	3D Printer-C
Max Printing Speed	(0.45,0.7,0.7,0.9,1,1)	(0,0.07,0.07,0.27,1,1)	(0.05,0.21,0.21,0.45,1,1)
Max Build Volume	(0.57,0.7,0.7,0.8,0.9,0.9)	(0.03,0.07,0.07,0.16,0.9,0.9)	(0.12,0.21,0.21,0.32,0.9,0.9)
Layer Resolution	(0.07,0.27,0.27,0.5,1,1)	(0.35,0.63,0.63,0.9,1,1)	(0.35,0.63,0.63,0.9,1,1)
Price	(0.16,0.27,0.27,0.38,0.9,0.9)	(0.48,0.63,0.63,0.76,0.9,0.9)	(0.48,0.63,0.63,0.76,0.9,0.9)

Positioning Precision	(0.15,0.35,0.35,0.63,1,1)	(0.03,0.15,0.15,0.35,1,1)	(0.03,0.15,0.15,0.35,1,1)

Step 4: The ranking weighted decision matrix obtained with the help of equation 1) is given in Table 7.

Table 7. Ranking weighted decision matrix.

Criteria	**Alternatives 3D Printers**		
	3D Printer-A	3D Printer-B	3D Printer-C
Max Printing Speed	7,81	4,22	4,98
Max Build Volume	5,30	7,39	7,39
Layer Resolution	5,80	4,65	4,65
Price	7,39	8,95	8,39
Positioning Precision	6,64	5,80	6,34

Step 5: With the help of eq.8 and 9, positive ideal solution and negative ideal solutions in Table 8 were obtained.

Table 8. Positive and negative ideal solutions.

Criteria	**Positive ideal solution**	**Negative ideal solution**
Max Printing Speed	7,81	4,22
Max Build Volume	7,39	5,30
Layer Resolution	4,65	5,80
Price	8,95	7,39
Positioning Precision	6,64	5,80

Step 6: With the help of eq.10 and 11, the distances of each alternative to the positive ideal solution (d^+) and the negative ideal solution (d^-) were calculated and the closeness indexes $C(x_i)$ were obtained with the help of eq.12 and given in Table 9.

Table 9. Distances to positive and negative ideal solution of each alternative and closeness indexes

Alternatives 3D Printers	d^+	d^-	$C(x_i)$	Ranking
3D Printer-A	2,85	3,69	0,56	1
3D Printer-B	3,69	2,85	0,44	3
3D Printer-C	2,90	2,75	0,49	2

The ranking of alternative 3D printers according to the closeness indexes are 3D Printer-A, 3D Printer-C, 3D Printer-B. Then, sensitivity analysis was performed according to the scenarios in Table 10 to determine whether the ranking of alternatives would change according to different criteria weights and the results were given in Figure 3.

Table 10. The scenarios combinations with different criteria weights**.**

Scenarios	Combinations
Scenario 1	Current
Scenario 2	Max Printing Speed Very Low, The Rest current
Scenario 3	Max Build Volume Very Low, The Rest current
Scenario 4	Layer Resolution Very Low, The Rest current
Scenario 5	Price Very Low, The Rest current
Scenario 6	Positioning Precision Very Low, The Rest current
Scenario 7	Max Printing Speed Very High, The Rest current
Scenario 8	Max Build Volume Very High, The Rest current
Scenario 9	Layer Resolution Very High, The Rest current
Scenario 10	Price Very High, The Rest current
Scenario 11	Positioning Precision Very High, The Rest current

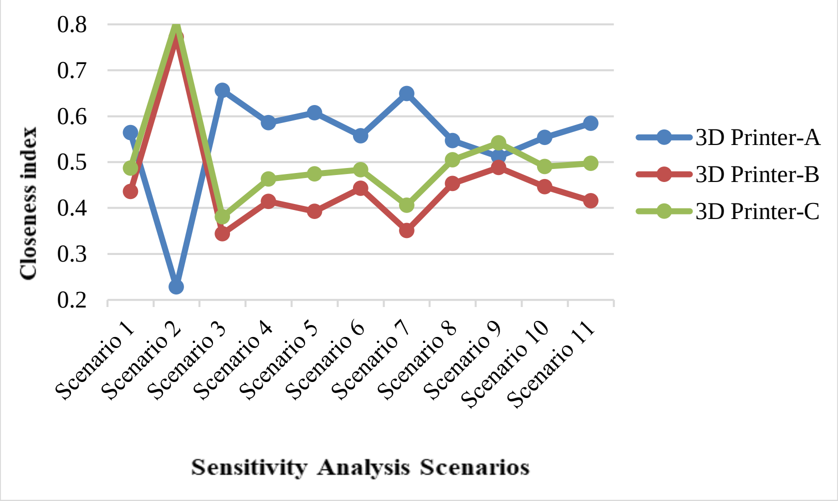

Figure 3. Results changes caused by the sensitivity analysis.

When the results obtained from the sensitivity analysis in Figure 3 are examined; in all scenarios except Scenario 2 and Scenario 9, the 3D Printer-A has been identified as the most suitable device. This result shows that the results obtained by the interval type-2 fuzzy TOPSIS method are sensitive and that the 3D Printer-A is the most suitable to buy.

4. Conclusion and evaluation

Rapidly evolving production technologies both shorten production processes and reduce production costs by finding a place in all sectors. Additive manufacturing, one of these technologies, is widely used in prototyping activities. 3D printers used for additive manufacturing have many features but devices that need to be taken into consideration during the purchase process. Because, there are many criteria that are effective in the process of buying 3D printers and it is a multi-criteria decision making problem. Therefore, it is useful to use multi-criteria decision-making methods to solve this problem.

In this study, the type-2 fuzzy TOPSIS method was used for the selection of the most suitable 3D printer that a company operating in the production sector would purchase for prototyping operations. After determining the criteria and alternatives that are effective in purchasing 3D printers, the most appropriate 3D printer is determined by evaluating the alternatives by applying the steps of the method. Then, sensitivity analysis was performed and the results obtained from the method were found to be sensitive. The interval type-2 fuzzy TOPSIS method used in this study provides more flexibility to decision makers according to the classical TOPSIS and fuzzy TOPSIS methods and provides more sensitive results. In this respect, the criteria and alternatives of the model used in this study can be changed/increased and used in other purchasing problems and in the solution of multi-criteria problems.

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