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3D Printer Technology Selection in Rapid Prototyping: A Spherical Fuzzy AHP Approach

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Abstract: *The aim of this study is to make the best technology decision for an enterprise in the automotive sector that plans to purchase a 3D printer for the purpose of obtaining rapid product prototypes. The study includes seven criteria as accuracy, complex design, surface quality, ease of use, throughput, material cost, and equipment cost, and three alternative technologies as fused deposition modeling (FDM), selective laser sintering (SLS), and stereolithography (SLA). The weighting of the criteria has been carried out by three experts in the product development department, and the evaluation of alternatives has been carried out by a team of 3D printer manufacturers. The spherical fuzzy analytic hierarchy process (SF-AHP) method is applied in the study. It's considered important for making the right technology decision in product development processes since this study seeks a solution to a real problem. As a result of the study, while the accuracy criterion is the highest priority, the ease of use of the selected printer is the least priority criterion. On the other hand, SLA 3D printer technology has been seen as the most ideal technology in terms of many criteria for prototyping automotive plastic material parts.*

Keywords: 3D Printer, Additive Manufacturing, Rapid Prototyping, Product Prototyping, Spherical Fuzzy AHP

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1. Introduction

Changing economic conditions and technological developments require some changes in the manufacturing industry. It is seen that traditional production methods are insufficient to meet some situations targeted by today's businesses and constantly diversifying customer expectations. These situations are affected the transformation and change of production methods used in the industry. The additive manufacturing method, which is considered a new industrial revolution, results in the flexible and rapid production of customized structures without spending a lot of money on changing production tools and processes (Dong-Woo et al., 2015).

There are many contributions that 3D printing technology provides to companies. It is difficult for traditional production technologies to manufacture products with different components and innovative materials due to their complex structure. 3D printing is a promising method for different applications in the manufacturing sector, with the mechanical properties of materials changing and diversifying greatly in recent years (Thompson et al., 2016). These methods have been developed for printing complex structures at very good resolutions. The method can provide materials with a high degree of geometric freedom and flexibility

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(Stampfl & Hatzenbichler, 2014). 3D printer technology provides manufacturing components with high production freedom quickly.

The 3D printing method is also referred to as additive manufacturing in production. Additive manufacturing also provides great advantages with its portable production features (Sun et al., 2022). Additive manufacturing technology is at a level to produce parts of various sizes from micro scale to macro scale. As industrial type large printers are used, small workshop type printers are also used. This completely depends on the purpose for which the technology is used. However, the fact that the technological tools used are often in portable sizes expands its usage areas in many respects. The use of area, which is especially important for manufacturers, provides an advantage with the use of this technology.

Printing large sizes of products (Attaran, 2017) and reducing the defects that may occur in printing increases with the development of this technology. The production of products in many different sizes demanded by businesses with the flexibility of technology will also facilitate a more comprehensive examination of these products. Such a situation will contribute to the elimination of errors that may occur in product design by detecting them beforehand. Thus, the 3D manufacturing system is likely to provide maximum material savings compared to traditional techniques. Greater material savings (Jandyal et al., 2022; Sun et al., 2022) and the ability to reduce waste (Hajare & Gajbhiye, 2022) are important advantages of 3D printing.

Additive manufacturing is a highly innovative technology. It is accepted that this technology will open new opportunities and contribute to many possibilities, especially for companies that want to increase production efficiency (Attaran, 2017). Additive manufacturing technology uses manpower especially in design, and does not include it in production processes. This also affects the fact that human errors are not experienced or are less experienced in the production processes. Thus, it greatly limits the unnecessary use of resources needed in production.

3D printing technology contributes to businesses gaining various benefits through their supply chains (Arbabian & Wagner, 2020). Businesses can quickly offer a wide variety of products to meet customer needs and expectations with this technology. This can enable the business to be agile in terms of supply chain and flexible production system (Jost & Süsser, 2019). In addition, additive manufacturing technology is in many ways a powerful tool to reduce complexity in the supply chain (Chen et al., 2021; Satzer & Achleitner, 2022; Verma et al., 2022). It has the potential to easily involve both its suppliers and customers in the design phase. It also has the agility to quickly meet any demand from its Stakeholders. This facilitates supply chain management.

It is important to use additive manufacturing technology for businesses that are aware of many opportunities. Due to the characteristics of the production method, it is known that applications are made for different purposes in many different sectors. Construction, food (Verma et al., 2022), biomechanics, medicine, aerospace (Aglawe et al., 2021; Shelare et al., 2021), clothing, jewelry, consumer goods (Mathew et al., 2020), automotive industry (Barbieri et al., 2017; Fabian et al., 2023) are the sectors where the application is intense. Increasing demand for 3D printed products increases the production of innovative materials in parallel (Waghmare et al., 2019). The continuous advancement of software and hardware in additive manufacturing is also affecting the expansion of the existing material palette (Sahu et al., 2020).

Originality in product design is one of the most important contributions of this technology (Hajare & Gajbhiye, 2022). 3D printing technology enables businesses to make different initiatives, try innovative product ideas, and design new products by improving existing models. In particular, it affects the fact that enterprises try new products by improving their existing product designs and provide great opportunities from design and production times. It has been observed that the process and delivery times of businesses are developing rapidly with 3D printing (Frohn-Sörensen et al., 2021; Sun et al., 2022). Since it is known that the product design stages take a lot of time, it can be predicted that the lead times of the products will be improved. Considering these, it can be stated that additive manufacturing is very important especially in terms of rapid prototyping and development (Dubar et al., 2017; Qadri, 2022; Fabian et al., 2023).

From this point of view, the objective of this study is to help businesses that are aware of the potential benefits of rapid prototyping to decide on the most suitable 3D printer technology. Various studies have been conducted in the literature for 3D printer selection decision (Agarwal et al., 2015; Choudhari & Patil, 2016; Khamhong et al., 2019; Prabhu & Ilangkumaran, 2019; Prabhu et al., 2021; Yeh & Chen, 2018). This study differs from other studies in many respects. This study is one of the original studies which compares production technologies (selective laser sintering [SLS], stereolithography [SLA], and fused deposition modeling [FDM]) for rapid prototyping according to various criteria of enterprises. Contrary to many studies in the literature, the criteria were not found to be of equal importance and different weight values were calculated for the criteria according to the evaluations of potential users. A contribution of the study to the literature is realized in terms of the sector in which the application is made.

Although the technology is known to be used in many different industries, additive manufacturing holds great promise for a wider application, especially in the automotive industry (Barbieri et al., 2017; Hajare & Gajbhiye, 2022). The decision to choose a 3D printer to be used for product design in the automotive industry was studied in the research of Prabhu & Ilangkumaran (2019), but the criteria used seem to be limited. For this reason, in this article, the application includes 3D printer technologies that an enterprise in automotive industry will prefer for rapid prototyping.

It is also important that the study it was conducted with two different focus groups. The fact that both the people who will use the technology and the experts who produce the technology are involved in simultaneously to the application makes the research more realistic. An important aspect of this study is the search for a solution to a real-life problem. Another contribution of the study is in terms of method. Although the analytical hierarchy process (AHP) is used in the relevant literature, it is a first with its spherical fuzzy analytical hierarchy process (SF-AHP). There is fuzzy in the study due to the inclusion of experts and the management of the process with linguistic expressions. Fuzzy AHP method also used spherical fuzzy sets because it can handle the uncertainty of the problem and the parameters can be assigned to a wider area.

The second part of the study presents a conceptual background on rapid prototyping and some 3D printing technologies. The third part includes information and stages about the spherical fuzzy AHP method used in the application section. The fourth section is the section in which the application made on an enterprise in the automotive sector is detailed. The fifth section includes the conclusions of the study.

2. Conceptual Backgorund of Rapid Prototyping and 3D Printer Selection

The desire of consumers to reach the products they demand in a short time and global competitiveness forced the industries to make some changes. Therefore the speed of the business bringing a product to market has become very important. This required businesses to make more efforts to reduce the production time they spent. One of the events that affect the production cycle times of the companies is undoubtedly the product design processes. At this stage, designers examine designs in many different geometries and decide on the most suitable product design for the purpose. However, contrary to popular belief, these processes are quite complex and time-consuming. In particular, the need to test models in complex geometries in a short time pushes businesses to seek new methods. Along with these, the need to shorten the cycle times of products (Sun et al., 2022) and increase production flexibility has required businesses to look for new techniques, processes, and methodologies. One of these solutions is rapid prototyping using additive manufacturing.

Prototyping is the production of a product model before it takes the final physical form of a product that has been decided to be produced. In product innovation processes for businesses, there’s usually no other option other than trial and error. Prototyping makes it easier to respond to this need in a short time. On the other hand, the main purpose of a prototyping process is to identify design defects such as compatibility or usability (Rayna & Striukova, 2016). Prototyping offers flexibility and adaptability to allow design teams to quickly test and evaluate different ideas, alternatives, and materials (Bellino et al., 2023). 3D printing technologies are important in terms of rapid prototyping of business models. It is expected that production preparation times will be greatly reduced, thus the time to market for new product designs will be shorter (Attaran, 2017). This will have an impact on meeting the demands of customers faster. Higher prototyping speed also contributes to a great improvement in service delivery, as it enables the establishment of "priority" services (Rayna & Striukova 2016). This technology enables flexible production that saves delivery time (Dankar et al., 2018).

Rapid prototyping, which is expressed as the rapid and short-term production of the prototype with generic technology, is also called 3D printing (Gross et al., 2014). The first application of additive manufacturing technology is known as rapid prototyping. Rapid prototyping is only one of the contributions of additive manufacturing. Recently, the method is emerged as a rapid production method in which small batches are produced (Qadri, 2022). When additive manufacturing technology was first used, rapid prototyping was mostly used by large companies because it required large costs. Small firms had very limited access to this technology. However, the drop in price as a result of various circumstances has affected the wider application of this technology. Even lower investment ($1000-4000) 3D printers are known to target small and medium sized (SMEs) and entrepreneurs who need rapid prototyping (Rayna & Striukova, 2016). The ability to quickly test ideas will significantly increase the speed of product development in the design and manufacturing industries. Rapid prototyping will likely have a huge impact on creativity, innovation, and competition (Rayna & Striukova 2016). Because of its low cost and rapid prototyping capability, additive manufacturing will help manufacturers develop new products with integrated material properties (Hajare & Gajbhiye, 2022).

When this technology was first developed, designers and architects in particular used 3D printing more because of its low cost and rapid prototyping potential. The potential effects of rapid prototyping were quickly realized and it was started to be widely used in many industries. Additive manufacturing, which is an advanced production technique with excellent design and high material usage, is widely used for rapid prototyping of components in the transportation sector (Günther et al., 2014). Rapid prototyping processes are especially preferred in the automotive industry (Rayna & Striukova 2016). If some changes are wanted to be made inside or outside of the car or the parts are expanded again with improved features, small differences in the model can be easily made with this technology (Fabian et al., 2023). Rapid prototyping contributes to faster and more flexible management of production.

The increase in technological developments and the rapid change in the economy have become a situation that changes the needs of people and their demands in this direction. Highly standardized homogeneous products attract less attention from consumers. Businesses are trying to optimize their high-quality and cost-effective product development cycles for market competitiveness, so rapid prototyping is starting to play an important role in the rapid product development cycle (Choudhari et al., 2016). Many different customized products emerge with 3D printing, and many manufacturers use this technology to customize products according to the individual needs of consumers (Attaran, 2017; Frohn-Sörensen et al., 2021; Sun et al., 2022). Because the demands of most of the consumers are constantly changing. Customization has emerged as a new production method for many manufacturers to attract customers. However, this poses a challenge for manufacturers due to the high costs of producing customized products for customers. Additive manufacturing provides a new way to achieve product customization by gradually changing production organization and innovation methods (Sun et al., 2022). In rapid prototyping, the product's rapid development, easy customization, and open source approach are the biggest advantages (Dubar et al., 2017).

Additive manufacturing contributes to the development of products in a single volume or in small quantities at a lower cost (Dankar et al., 2018; Hajare & Gajbhiye, 2022). Rapid prototyping methods are highly preferred, especially in cases where the development stages are expensive and take a lot of time (Dubar et al., 2017). It is known that the use of this technology greatly reduces the costs incurred in the product development process of enterprises. It is an important application that saves resources especially for small series production of enterprises. (Frohn-Sörensen et al., 2021). On the other hand, the cost benefit is the lack of additional costs in requirements such as mold making and tooling for customized products. Components of multiple parts can be produced economically without redesigned assembly with better performance (Gibson et al., 2015).

On the other hand, the decision to choose a 3D printer is a critical issue. Additive manufacturing is a technology that enables the production of objects by accumulating materials layer by layer according to the three-dimensional model files designed on the computer. The machines that provide printing in this technology are 3D printers. If a machine has three features: three-dimensional, additive and layer-based, it is considered a 3-D printer (Jandyal et al., 2022). 3D printing starts with the basic design of the desired part (Raina et al., 2021). A product is created by combining one layer wiht the other by reading this design by a three-dimensional printer.

Different methods in 3D printer technologies used in rapid prototyping may vary depending on the work involved in the process, the benefits and disadvantages it will provide, the materials to be used, and various features such as accuracy, resolution, and efficiency. Ultra flexibility and high precision of this technology are also among the selection criteria (Sun et al., 2022). Products with complex geometry, which can be produced with the high flexibility of additive manufacturing technology, are the situations that users expect most (Tomassoni et al., 2018). It is important that 3D printers have great potential to produce complex products. Conventional forming techniques are fast and accurate for the production of large lot sizes, but insufficient due to expensive tooling (Frohn-Sörensen et al., 2021). The inadequacy here can be easily solved with 3D printing technologies. Many different additive manufacturing technologies have been developed to meet the need for high resolution printing of complex models (Jandyal et al., 2022).

One of the sought-after features is the accuracy of products produced with 3D printers (Cetinkaya et al., 2017). It is very important that the product determined during the design phase is produced with the expected features and dimensions using 3D printers. The fact that the features and purposes in a product meet the expectation will be measured by the accuracy of the manufactured product. Compared to traditional production, 3D printing technology used in rapid prototyping is known to improve this situation (Vaezi et al., 2013). Different techniques can be preferred in order to produce a correct product. The durability of objects produced with 3D printing technology is also a critical issue (Byun & Lee, 2005) because the durability of the part is an important performance indicator.

An important issue in the selection of 3D printers is the quality of the products produced (Choudhari & Patil, 2019; Rayna & Striukova, 2016). There may be some concerns in rapid prototyping to produce quality products. There are problems such as solution leaks, which are very common in products printed with 3D printers, it is very important to be able to solve them and to provide high quality well-sealed objects (Stefano et al., 2022). In the rapid prototyping process, surface quality is important as it directly affects the quality of the product (Chen & Zhao, 2016; Vaezi et al., 2013). Surface quality is essential for better functionality, appearance, and cost reduction by reducing post-production processes (Qadri, 2022). Differentiation in the surface quality of the objects to be produced according to the preferred 3D printers is extremely possible. This feature greatly affects the users' choice of 3D printers.

One of the most important criteria for 3D printer selection is cost. Both the cost of equipment and the cost of materials used in printers limit the use of this technology. One of the biggest obstacles for 3D printers is seen as equipment costs (Attaran, 2017; Beliatis et al., 2022; Michielsen et al., 2019; Micińsk et al., 2021). Demands from manufacturers have led to the need to research and develop new techniques for more cost-effective 3D printing (Mani et al., 2022). Material cost is also a significant factor affecting the selection of potential users (Attaran, 2017; Hajare & Gajbhiye, 2022; Jandyal et al., 2022). The cost of materials used in 3D printing technology must be carefully considered.

3D printers are among the most common tools that make rapid prototyping more accessible, economical, and faster (Bellino et al., 2023). It is an important technology that has made great progress since the first time it emerged and still continues to develop. The diversity of 3D printers makes it difficult for users to choose a suitable 3D printer (Rong et al., 2018) and this topic is considered to be insufficient in the literature (Chen & Wu, 2021). When the 3D printer selection research in the literature is examined, it’s seen that it’s very limited.

Most studies in the literature have focused on the selection of 3D printing technologies suitable for special applications (Peko et al., 2015; Shi et al., 2017; Robinson et al., 2019). Roberson et al. (2013) examined the 3D printer selection decision in terms of four criteria: construction time, price, material costs, and quality of the manufactured products. Agarwal et al. (2015) used both an analytical network process and a similarity-based method to rank twelve 3D printer alternatives for educational institutions according to volume, speed, layer thickness, extruder capacity, price, and material price criteria. The researchers also weighted the six criteria they used. Choudhari and Patil (2016) compared SLS, SLA, and FDM technologies in terms of material draw rate, dimensional accuracy, time, cost and surface quality. The weights of the criteria were not calculated in the study.

Yeh and Chen (2018) applied a fuzzy AHP approach to 3D printing application to prioritize four main critical success factors: technology, organization, environment, and cost. The researchers performed the application on Taiwanese manufacturing companies. Khamhong et al. (2019) evaluated the factors related to the selection of 3D printers with three main criteria: product, material, and machine. The product criterion was examined in terms of accuracy, finish surface, cost, time and smoothness. The material criterion was examined in terms of tensile strength and elongation, and the machine criterion was examined in terms of printer cost, maximum build size, and user preference. In this study, six people, three of whom are technical experts and three of whom are users, evaluated, and Fuzzy AHP was used for criterion weighting.

Prabhu and Ilangkumaran (2019) investigated the proficiency of ten different 3D printers to produce automotive parts and evaluated the issue on the criteria of volume, printing speed, layer thickness, extruder, machine cost, and material cost. The criteria in this study are not weighted in any way. Prabhu et al. (2021) evaluated the criteria such as maximum print volume, processing speed, minimum thickness, extruder capacity, printer cost, and filament material cost in the 3D printer selection problem. Rakhade et al. (2021) performed on physical properties, economic evaluation, and operational requirements for 3D printer model selection for educational purposes.

In the relevant literature, it is often desired to make a decision to choose among different model three-dimensional printers. In this study, SLS, FDM, and SLA techniques from 3D printing technologies are included. These technologies were determined to be widely used and therefore all of them were chosen for the study. Each of these technologies are manufacturing technology used in rapid prototyping processes.

SLS (Selective Laser Sintering)

SLS is based on selective laser sintering of layers of a three-dimensional model prepared in a computer environment. A 3D model is produced using design programs and the design is sent to the printer. The straightening roller spreads the powder material across the platform. Depending on the surface tip and fusion type, the formation of layers takes place with the help of CO_2 or Nitrogen lasers, and various chemical compound powders are used in this process (Jandyal et al., 2022). High power CO_2 laser is used in industrial SLS systems. When the process for one layer is finished, the next layer is started. The powders used must be heated to a temperature below the melting point of the equivalent material. The excess powder remaining outside the sintered powder in each layer acts as a support for the sintered section.

Stainless steel, chrome nickel, various metals, and plastic materials such as polyamide can be used in the method. Because various types of laser can be used to sinter different materials in SLS, this technology has become central to many fields such as medical and industrial applications (Li et al., 2021; Tareq et al., 2021). The SLS method is seen as an opportunity with advances in material selection for standard production methods such as aerospace, automobile, and biomedical applications (Jain et al., 2006).

SLA (Stereolithography)

SLA technology is the solidification of a liquid photopolymer material with light to obtain a product layer by layer. In the first stage, a 3D image of the object is created as in other 3D printing technologies and the design is transferred to the 3D printer. In SLA imprinting, the stereolithography resin is deposited layer by layer according to the prerequisite model and it is polymerized by UV laser or other light sources at that time (Weng et al., 2016). Since photopolymers are sensitive to ultraviolet light, the resin photochemically solidifies and thus layers are formed (Fouassier, 2003). This process is repeated for each layer until the desired product is completed. Although SLS and SLA technologies are mixed due to the use of laser, the powder material is used in SLS technique, and fluid material is used in SLA technique.

The SLA technique was developed to allow them to build prototypes of their designs more efficiently than time (Gibson & Jorge Bártolo, 2011). When the materials used in SLA are examined, it is seen that there can be many different densities, such as glass, ceramic, and plastic, as well as soft or hard materials (Formlabs, Access Date: 13.06.2023). Innovative applications continue to be developed with the development of the method, especially in the automotive sector (Jacobs, 1992).

FDM (Fused Deposition Modeling)

FDM is a procedure that uses mostly thermoplastic materials brought to the melting point and pushes the materials out layer by layer (Chadha et al., 2019). In this method, adjacent layers are consolidated to each other, and the deposition is completed by the extruder (Haq et al., 2021). The thermoplasticity of the polymer filament is important because it allows the materials to fuse together in printing and solidify at room temperature after printing (Ngo et al., 2018). In this system, the temperature of the outside environment and the temperature of the printed material are important. As the printing temperature is just above the melting point of the material and the temperature of the environment is necessarily lower than the melting point, the solid form of the object can be formed (Kading & Straub, 2015).

Technologies such as FDM and STL have been becoming affordable for small businesses and individuals over the past few years. It is especially effective for the development of allowing the use of many different materials. Many different types of materials are used for FDM printing, such as nylon, ABS, PLA, and polycarbonate (Warnier et al., 2014). FDM technology has been increasingly used in industries as diverse as medical, electronics, and automobiles (Shafaat & Rezaei, 2021).

3. Method

In this study, the Spherical Fuzzy AHP approach is preferred to weight the criteria and to make the most appropriate technology selection decision. First, fuzzy logic-based AHP methods are preferred because the traditional AHP approach is insufficient to deal with uncertainty. The spherical fuzzy AHP method is also used because it can be assigned to the parameters of the membership function with a wider area, and it can handle the uncertainty of the problem in decision making by using the degree of hesitation (Kahraman & Kutlu Gündogdu, 2018; Kutlu Gündogdu & Kahraman, 2019). In addition, the simplicity and ease of use of the method has also been important. On the other hand, since the Spherical Fuzzy AHP approach has not been used in the relevant literature, it is desired to contribute to the literature from a methodological point of view.

AHP, which is one of the multi-criteria decision making methods, was developed by Saaty in 1980. The AHP method basically evaluates alternatives according to certain criteria. In AHP, pairwise comparisons are studied according to decision makers to obtain priority matrices. The method, which is based on pairwise comparisons and eigenvectors, is widely used due to its easy implementation, understanding, and interpretation of results (Otay, 2023). In the classical analytical hierarchy process, the evaluations of the decision makers are made with exact figures. There are several limitations of the classical AHP for this reason. However, it is not possible to make precise evaluations in some cases, so a fuzzy environment is created. The fuzzy approach helps to overcome the disadvantages of the classical AHP approach (Singer & Ozsahin, 2022).

Fuzzy logic, which provides a mathematical power in this uncertain environment, is used when decision makers cannot express their evaluations with exact numbers. Uncertainty can be modeled with fuzzy logic, and the relevant situation can be estimated approximately under these conditions. After the introduction of ordinary fuzzy sets by Zadeh (1965), fuzzy sets began to be developed in many areas. Extensions of ordinary three-dimensional fuzzy sets (heuristic, pythagorean and neutrophic sets) aim to more clearly collect the statements of decision makers (Kutlu Gündogdu & Kahraman, 2020). These fuzzy versions have started to be used in order to use the classical AHP in uncertain environments. One of the versions of the AHP method is the Spherical Fuzzy AHP (SF-AHP).

There is a fact that spherical fuzzy sets are based on. The concern of decision makers can be expressed independently of membership and non-membership degrees in these clusters. (Ozdemir, 2021). The method was developed in 2019 by Kutlu Gündogdu and Kahraman as a combination of pythagorean fuzzy sets and neutrophic fuzzy sets. The idea behind spherical fuzzy sets is that the membership function of decision makers will be identified on a spherical surface (Ozdemir, 2021). Thus, the parameters of the function can be assigned to a wider area independently (Kutlu Gündogdu & Kahraman, 2019).

Since SF-AHP is a fairly new method, it has been used in limited studies. Yildiz et al. (2020) used the method to define the importance levels of criteria that are effective in employee retention and to evaluate career management activities. Oztaysi et al. (2020) focused on Industry 4.0 project prioritization and evaluated five projects with the SF-AHP approach according to 4 main criteria.

Looking at the study published in 2021, SF-AHP technique was used to support the distribution site selection problem of perishable agricultural products by Kieu et al. (2021), to determine factors affecting individuals' behavioral vaccination intention against COVID-19 by Nguyen et al. (2021a), to analyze public transport development by Duleba et al. (2021), to measure the importance of various criteria for preventing the spread of COVID-19 by Nguyen et al. (2021b).

In 2022, an increase was observed in the studies using the Spherical Fuzzy AHP approach. The Spherical Fuzzy AHP technique was used to evaluate the sustainable industrialization performance of countries and to determine the importance weights of 16 sub-criteria by Candan and Cengiz Toklu (2022), to investigate the risks of sustainable fishery products by Nguyen (2022), to evaluate four food waste treatment options, taking into account four criteria (infrastructure, government, economic and environmental) and thirteen sub-criteria to select the best food processing option by Buyuk and Temur (2022). Mangla et al. (2022) applied the SF-AHP technique to identify the application of blockchain technology to the tea supply chain, and Singer and Ozsahin (2022) used this method to prioritize the five main criteria and twenty sub-criteria in laminate flooring selection from the perspective of experts.

On the other hand, SF-AHP technique was used to establish an Industry 4.0 performance measurement and scoring process in SME manufacturing companies by Ozdemir (2022), to select the best fertilizer supplier to achieve sustainable development goal by Wang and Van Thanh (2022), to evaluate criteria to determine a sustainable supplier for the steelmaking industry by Nguyen et al. (2022), to evaluate the contractor's performance against project performance parameters (cost, scheduling, quality, leadership and change management) by Abdulkareem and Erzaij (2022), to select the sustainable energy source for the industrial complex in Vietnam by Van Thanh (2022). Finally, Otay (2023) used the method for a technology center location evaluation problem, which has a strategic and complex structure on the success and performance of engineering firms.

The steps of the method are as follows (Kutlu Gündogdu & Kahraman, 2019; Ozdemir, 2021):

Step 1: The hierarchical structure of the problem is created. The structure applies to all versions of the analytic hierarchy process. At this stage, all criteria and alternatives are determined.

Step 2: SF-AHP pairwise comparison matrix is created using linguistic expressions. Binary decision matrices are formed in line with the ideas and opinions of decision makers. Linguistic variables and their fuzzy number equivalents used for pairwise comparisons are shown in Table 1.

Table 1. Linguistic Criteria Used for Pairwise Comparisons

Linguistic Variable	Spherical Fuzzy Number $(\boldsymbol{\mu}, \boldsymbol{v}, \boldsymbol{\pi})$	Score Index (SI)
Absolutely more importance (AMI)	(0.9, 0.1, 0)	9
Very high importance (VHI)	(0.8, 0.2, 0.1)	7
High importance (HI)	(0.7, 0.3, 0.2)	5
Slightly more (high) importance (SMI)	(0.6, 0.4, 0.3)	3
Equally importance (EI)	(0.5, 0.4, 0.4)	1
Slightly low importance (SLI)	(0.4, 0.6, 0.3)	1/3
Low importance (LI)	(0.3, 0.7, 0.2)	1/5
Very low importance (VLI)	(0.2, 0.8, 0.1)	1/7
Absolutely low importance (ALI)	(0.1, 0.9, 0)	1/9

Source: Kutlu Gündogdu & Kahraman (2020).

The SI value in Table 1 is obtained using Equation 1.

$$SI = \sqrt{100 * \left[\left(\boldsymbol{\mu}_{\widetilde{\boldsymbol{A}_s}} - \pi_{\tilde{A}_s}\right)^2 + \left(\boldsymbol{v}_{\tilde{\boldsymbol{A}}_s} - \pi_{\tilde{A}_s}\right)^2\right]} \quad (1)$$

Step 3: Consistency is analyzed for each pairwise comparison matrix. Linguistic values in the pairwise comparison matrix are converted into score indices using Equation (1). For example, when a linguistic term is "High importance (HI)", its numerical equivalent is translated to 5 according to Table 1.

The consistency ratio (CR) is calculated by applying the consistency test, first using Equation (2), then Equation (3) and (4). At the same time, Table 2 is used to apply Equation (4). According to Saaty, if the consistency ratio is greater than 0.1, the pairwise comparison matrix needs to be revised.

λmax is the maximum eigenvalue of the matrix, and n is the number of criteria. Its calculation is as follows:

$$\lambda max = \frac{1}{n} \sum_{i=1}^{n} \frac{\sum_j^n aj*wj}{wi} \quad (2)$$

$$CI = \frac{\lambda_{av} - n}{n-1} \quad (3)$$

Table 2. RI Values

1	2	3	4	5	6	7	8	9	10
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Karagiannidis et al. (2010).

$$CR = \frac{CI}{RI} \quad (4)$$

Step 4: The global fuzzy local weights of the criteria and alternatives are calculated. The spherical weighted arithmetic mean (SWAM) equation in Equation (5) is used to calculate spherical fuzzy weights.

$$SWAM=[1-\prod_{i=1}^{n}(1-\mu_{A_{si}}^2)^{wi}]^{1/2}, \prod_{i=1}^{n} \nu_{A_{si}}^{wi}), [\prod_{i=1}^{n}(1-\mu_{A_{si}}^2)^{wi} - \prod_{i=1}^{n}(1-\mu_{A_{si}}^2 - \pi_{A_{si}}^2) \quad (5)$$

Step 5: The resulting fuzzy weights are clarified. Equation (6) is used for this.

$$S(wj) = \sqrt{100 * \left[\left(3\boldsymbol{\mu}_{\widetilde{A_s}} - \frac{\pi_{\tilde{A}_s}}{2}\right)^2 + \left(\frac{v_{\tilde{A}_s}}{2} - \pi_{\tilde{A}_s}\right)^2\right]} \quad (6)$$

Step 6: The weight values of the global weights and alternatives are calculated.

Step 7: Alternatives are listed according to their weight values.

4. Application

This study focuses on the choice of 3D printing technology that a manufacturer will use for rapid prototyping of plastic parts during product development. The automotive industry is currently among the leading segments of the emerging economy. The application is based on the real decision problem of a manufacturer operating in the automotive industry. The company in the application is a medium-sized company that produces parts in the automotive supply industry in Ankara.

4.1. Selection of Decision Makers

The criteria in the study were decided by expert opinions. The criteria were determined by three experts of the enterprise. They work in the business's product development department. Also, since the people who will use the technology are the same people, the selection criteria were suggested by them. Expertise and experience were given importance in the selection of decision makers. One of these three decision makers is the product development manager, who has worked in different companies and has a total of 12 years of work experience. This person is also an industrial product design engineer. The second decision maker is the engineer who works as the assistant product development manager and has nine years of total work experience. The final decision maker is a software engineer with seven years of work experience, who has been actively involved in modeling projects and closely follows technological developments. They will make the selection decision for the 3D printer that the company plans to purchase to use in the rapid prototyping process. The experts made linguistic evaluations on the criteria.

The second focus group of the application consists of four experts who produce the technology. It is these people who will decide how the criteria will be met by alternatively recommended 3D printers. Each of the participants are male employees of companies producing 3D printers in Turkey. One of these people is also a person who has an academic career and gives training to various companies on the application of this technology. All of the experts have work experience ıf five years or more.

4.2. Identification of Criteria and Alternatives

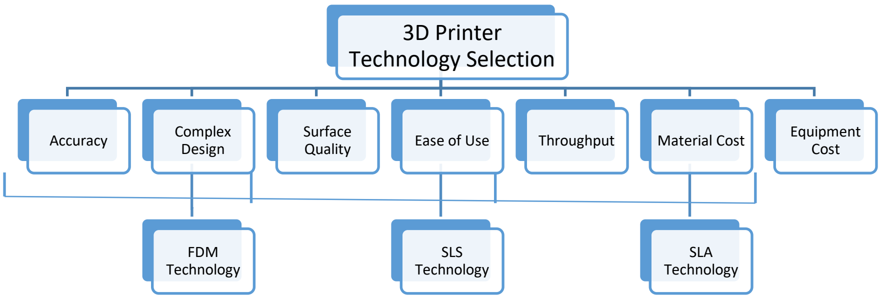
The list of criteria determined by the expert group of three people in the study is as follows: C_1: Accuracy, C_2: Complex design, C_3: Surface quality, C_4: Ease of use, C_5: Throughput, C_6: Material cost, C_7: Equipment cost.

In total, seven criteria were evaluated by decision-making experts according to technological diversity. There are three alternative printer technologies in the study, namely FDM (A_1), SLS (A_2), and SLA (A_3). In the selection of these technologies, the ability of rapid prototyping techniques to meet the manufacturing needs in the automotive industry has been effective. The comparison of alternatives according to the relevant criteria was expressed by a team of four in a unanimous opinion.

4.3. Results

Step 1: The seven main criteria in the study and the hierarchical structure of the three alternatives are shown in Figure 1.

Figure 1. Hierarchical Structure of the Problem



Step 2: The spherical fuzzy AHP pairwise comparison matrix is created by using linguistic expressions by the expert who plans to use the technology. Table 1 was used for this.

Table 3. Pairwise Comparison Matrix of Criteria

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	EI (0.5,0.4,0.4)	HI (0.7,0.3,0.2)	SMI (0.6,0.4,0.3)	AMI (0.9,0.1,0.0)	VHI (0.8,0.2,0.1)	VHI (0.8,0.2,0.1)	EI (0.5,0.4,0.4)
C_2	LI (0.3,0.7,0.2)	EI (0.5,0.4,0.4)	SLI (0.4,0.6,0.3)	HI (0.7,0.3,0.2)	SMI (0.6,0.4,0.3)	SMI (0.6,0.4,0.3)	LI (0.3,0.7,0.2)
C_3	SLI (0.4,0.6,0.3)	SMI (0.6,0.4,0.3)	EI (0.5,0.40,0.4)	VHI (0.8,0.2,0.1)	HI (0.7,0.3,0.2)	HI (0.7,0.3,0.2)	SLI (0.4,0.6,0.3)
C_4	ALI (0.1,0.9,0.0)	LI (0.3,0.7,0.2)	VLI (0.2,0.8,0.1.)	EI (0.5,0.40,0.4)	LI (0.3,0.7,0.2)	LI (0.3,0.7,0.2)	VLI (0.2,0.8,0.1)
C_5	VLI (0.2,0.8,0.1)	SLI (0.4,0.6,0.3)	LI (0.3,0.7,0.2)	HI (0.7,0.3,0.2)	EI (0.5,0.4,0.4)	EI (0.5,0.4,0.4)	VLI (0.2,0.8,0.1)
C_6	VLI (0.2,0.8,0.1)	SLI (0.4,0.6,0.3)	LI (0.3,0.7,0.2)	HI (0.7,0.3,0.2)	EI (0.5,0.4,0.4)	EI (0.5,0.4,0.4)	VLI (0.2,0.8,0.1)
C_7	EI (0.5,0.4,0.4)	HI (0.7,0.3,0.2)	SMI (0.6,0.4,0.3)	VHI (0.8,0.2,0.1)	VHI (0.8,0.2,0.1)	VHI (0.8,0.2,0.1)	EI (0.5,0.4,0.4)

CR=0.069

The alternatives for each criterion were compared in pairs and evaluated from Table 4 to Table 10 by the three-dimensional printer technology producer group.

Table 4. Pairwise Comparison of Alternatives according to Accuracy Criteria

C_1	A_1	A_2	A_3
A_1	EI (0.5,0.4,0.4)	SLI(0.4,0.6,0.3)	SLI(0.4,0.6,0.3)
A_2	SMI(0.6,0.4,0.3)	EI (0.5,0.4,0.4)	EI (0.5,0.4,0.4)
A_3	SMI(0.6,0.4,0.3)	EI (0.5,0.4,0.4)	EI (0.5,0.4,0.4)

CR=0.00

Table 5. Pairwise Comparison of Alternatives according to Complex Design Criteria

C_2	A_1	A_2	A_3
A_1	EI (0.5,0.4,0.4)	LI (0.3,0.7,0.2)	SLI(0.4,0.6,0.3)
A_2	HI (0.7,0.3,0.2)	EI (0.5,0.4,0.4)	SMI(0.6,0.4,0.3)
A_3	SMI(0.6,0.4,0.3)	SLI(0.4,0.6,0.3)	EI (0.5,0.4,0.4)

CR=0.021

Table 6. Pairwise Comparison of Alternatives according to Surface Quality Criteria

C_3	A_1	A_2	A_3
A_1	EI (0.5,0.4,0.4)	LI(0.3,0.7,0.2)	VLI (0.2,0.8,0.1)
A_2	HI (0.7,0.3,0.2)	EI (0.5,0.4,0.4)	SLI(0.4,0.6,0.3)
A_3	VHI (0.8,0.2,0.1)	SMI (0.6,0.4,0.3)	EI (0.5,0.4,0.4)

CR=0.036

Table 7. Pairwise Comparison of Alternatives according to Ease of Use Criteria

C_4	A_1	A_2	A_3
A_1	EI (0.5,0.4,0.4)	SMI (0.6,0.4,0.3)	EI (0.5,0.4,0.4)
A_2	SLI(0.4,0.6,0.3)	EI (0.5,0.4,0.4)	SLI(0.4,0.6,0.3)
A_3	EI (0.5,0.4,0.4)	SMI (0.6,0.4,0.3)	EI (0.5,0.4,0.4)

CR=0.00

Table 8. Pairwise Comparison of Alternatives according to Thoughput Criteria

C_5	A_1	A_2	A_3
A_1	EI (0.5,0.4,0.4)	SLI(0.4,0.6,0.3)	EI (0.5,0.4,0.4)
A_2	SMI (0.6,0.4,0.3)	EI (0.5,0.4,0.4)	SMI (0.6,0.4,0.3)
A_3	EI (0.5,0.4,0.4)	SLI(0.4,0.6,0.3)	EI (0.5,0.4,0.4)

CR=0.00

Table 9. Pairwise Comparison of Alternatives according to Material Cost Criteria

C_6	A_1	A_2	A_3
A_1	EI (0.5,0.4,0.4)	LI(0.3,0.7,0.2)	SLI(0.4,0.6,0.3)
A_2	HI (0.7,0.3,0.2)	EI (0.5,0.4,0.4)	SMI (0.6,0.4,0.3)
A_3	SMI (0.6,0.4,0.3)	SLI(0.4,0.6,0.3)	EI (0.5,0.4,0.4)

CR=0.164

Table 10. Pairwise Comparison of Alternatives according to Equipment Cost Criteria

C_7	A_1	A_2	A_3
A_1	EI (0.5,0.4,0.4)	VHI (0.8,0.2,0.1)	HI (0.7,0.3,0.2)
A_2	VLI (0.2,0.8,0.1)	EI (0.5,0.4,0.4)	SLI(0.4,0.6,0.3)
A_3	LI(0.3,0.7,0.2)	SMI (0.6,0.4,0.3)	EI (0.5,0.4,0.4)

CR=0.036

Step 3: The consistency ratio was calculated using the classical method. CR values are shown below tables. This shows that the pairwise comparison matrix is consistent. For this, the SI values shown in Table 1 were used by using Equation (1). Then, CR values were reached by using Equation (2), Equation (3), Table 2 and Equation (4), respectively. For a better understanding, the CR value for the matrix in Table 3, which was obtained as a result of the pairwise comparison of the main criteria, was calculated as follows:

Table 11. Calculation of the Consistency Ratio of Criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	Geo M.	EV	$a * wj$	λ
C_1	1	5	3	9	7	7	1	3.51	0.325	2.37	7.305
C_2	1/5	1	1/3	5	3	3	1/5	0.93	0.086	0.64	7.421
C_3	1/3	3	1	7	5	5	1/3	1.79	0.165	1.23	7.413
C_4	1/9	1/5	1/7	1	1/5	1/5	1/7	0.21	0.019	0.16	8.193
C_5	1/7	1/3	1/5	5	1	1	1/7	0.49	0.045	0.34	7.518
C_6	1/7	1/3	1/5	5	1	1	1/7	0.49	0.045	0.34	7.518
C_7	1	5	3	7	7	7	1	3.39	0.313	2.34	7.448
$\sum$=								10.8	1		Av: 7.545

Using Equation (3), CI = $\frac{\lambda_{max}-n}{n-1} = \frac{7.545-7}{6}$ = 0.091

After the CI value reached, in the direction of Equation (4);

CR = $\frac{CI}{RI} = \frac{0.091}{1.32}$ = 0.069 (Since the CR value is less than 0.1, it can be stated that the matrix is consistent.)

Table 12. CR Values of Criteria

Criteria	**Table number**	**CR**
For C_1	Table 4	CR=0.00
For C_2	Table 5	CR=0.021
For C_3	Table 6	CR=0.036
For C_4	Table 7	CR=0.00
For C_5	Table 8	CR=0.00
For C_6	Table 9	CR=0.164
For C_7	Table 10	CR=0.036

As shown in Table 12, each of the CR values of the criteria is less than 0.1. According to Saaty, the pairwise comparison matrix is consistent, with the consistency ratio less than 0.1.

Step 4-5: Global fuzzy local weights of seven criteria and alternatives are calculated, then the weight values are clarified.

Equation (5) was used for the local weight values (SWAM) of the values in Table 3 to calculate the global weights of the criteria. These values are in the first column of the table below. Then, Equation (6) was applied to clarify the fuzzy values and the values were shown in the second column. Finally, the weight values (w) of the criteria were calculated by dividing the S(wj) value of the criteria by the total S(wj) value.

Table 13. Calculation of Weight Values of Criteria

	SWAM	**$S(w_j)$**	**W**
C_1	(0.730, 0.310, 0.264)	20.649	0.20
C_2	(0.520, 0.54, 0.282)	14.219	0.14
C_3	(0.620, 0.435, 0.275)	17.333	0.17
C_4	(0.300, 0.755, 0.210)	7.784	0.07
C_5	(0.450, 0.634, 0.274)	12.181	0.12
C_6	(0.450, 0.634, 0.274)	12.181	0.12
C_7	(0.700, 0.317, 0.266)	19.712	0.19
Total:		104.062	1

In Table 13, the weight values of the criteria were calculated. This table allows us to evaluate from the most effective criterion to the least effective criterion in the 3D printer technology selection decision by the experts. The most prioritized criterion by the first expert group is seen as the C1 accuracy criterion with a weight value of 0.20. At the same time, it can be stated that accuracy criteria is the most important criterion with a 20% effect rate among all criteria. The second highest weighted criterion is the C7 equipment cost with a weight value of 0.19. In other words, equipment cost has a 19% effect rate in selecting 3D printers among all criteria. The third most important criterion emerged as surface quality with a weight ratio of 0.17.

After the weight values of the criteria were obtained, the weight values of the alternatives were calculated.

Table 14. Calculation of Weight Values of Criteria

		SWAM	**S(w_j)**	**W**
C_1	A_1	(0.44, 0.55, 0.34)	11.43	0.29
	A_2	(0.54, 0.40, 0.37)	14.26	0.36
	A_3	(0.54, 0.40, 0.37)	14.26	0.36
C_2	A_1	(0.41, 0.59, 0.31)	10.78	0.26
	A_2	(0.61, 0.37, 0.31)	16.79	0.41
	A_3	(0.51, 0.48, 0.34)	13.65	0.33
C_3	A_1	(0.36, 0.68, 0.27)	9.532	0.22
	A_2	(0.56, 0.46, 0.31)	15.27	0.35
	A_3	(0.67, 0.35, 0.30)	18.48	0.43
C_4	A_1	(0.54, 0.40, 0.37)	14.26	0.36
	A_2	(0.44, 0.55, 0.34)	11.43	0.29
	A_3	(0.54, 0.40, 0.37)	14.26	0.36
C_5	A_1	(0.47, 0.48, 0.37)	12.25	0.31
	A_2	(0.57, 0.40, 0.34)	15.42	0.39
	A_3	(0.47, 0.48, 0.37)	12.25	0.31
C_6	A_1	(0.41, 0.59, 0.31)	10.78	0.26
	A_2	(0.61, 0.37, 0.31)	16.79	0.41
	A_3	(0.51, 0.48, 0.34)	13.65	0.33
C_7	A_1	(0.70, 0.31, 0.27)	19.52	0.45
	A_2	(0.39, 0.65, 0.30)	10.3	0.24
	A_3	(0.49, 0.54, 0.31)	13.17	0.31

The clarified weight values of the alternatives for each criterion are shown in Table 14. For example, the most suitable printer selection for the accuracy criterion (C1) is seen as both SLA and SLS. The most suitable printer technology for the complex design criterion (C2) is SLS, and the most suitable technology for the surface quality criterion (C3) is SLA. However, alternatives cannot be selected according to the current table. Because, as seen for each criterion, the best choice decision may change. Therefore, the final global weight value is needed for each alternative.

Step 6: Global weights were obtained using the clarified local weights. Table 14 and Table 15 were used for this purpose.

Table 15. Global Weight Values of Alternatives

Criteria	Criterion weights	A_1	A_2	A_3
C_1	0.20	0.29	0.36	0.36
C_2	0.14	0.26	0.41	0.33
C_3	0.17	0.22	0.35	0.43
C_4	0.07	0.36	0.29	0.36
C_5	0.12	0.39	0.31	0.39
C_6	0.12	0.26	0.41	0.33
C_7	0.19	0.45	0.24	0.31
Alternative weights		0.320	0.323	0.362

In Table 15, global weight values were obtained for each alternative by considering the criteria weights. According to Table 15, FDM and SLS resulted in 32% and SLA resulted in 36% in the selection of the most appropriate technology as requested by the manufacturers. It is seen that the results regarding the selection of each technology do not differ greatly from each other. This result shows once again that FDM and SLS technology can also be used in rapid prototyping. However, when looking at the final result, SLA technology should be seen as the most suitable technology that the manufacturer in the automotive industry should choose for the purpose of obtaining rapid prototypes.

5. Conclusion

The use of 3D printer technology in the production processes of businesses has become a trending practice especially in recent years. The use of 3D printer technology, especially in product design processes, is of great importance due to the unique benefits it provides to businesses in many ways. Some technologies can offer several advantages such as high resolution, high strength, high accuracy, and good surface quality. It could also be argued that this has changed businesses' cost structure and value capture, as rapid prototyping has become affordable with new technologies. For this reason, businesses need an effective decision-making process to decide to use 3D printer technology in rapid prototyping.

In this study, it is aimed to decide on the most appropriate 3D printer technologies that a manufacturer in the automotive industry plans to purchase for rapid prototyping in product design processes. In other words, the aim of this study is to evaluate and rank additive manufacturing technologies based on a number of criteria that can facilitate purchasing decisions for 3D printers that businesses will use in the rapid prototyping process. The study highlights the differences and similarities between additive manufacturing technologies and compares the criteria in this direction. The research is a real life problem because the criteria are chosen by the group that will use the technology, and the printers are evaluated by the expert who produces the technology according to these criteria.

In the application section, the spherical fuzzy AHP method was used and it can be stated that this method contributed to the literature. The method's attainment of weight values by taking into account the consistency ratios provided confidence in the resulting data. Looking at the CR values, it is seen that every result is consistent.

There are seven criteria in the study: accuracy, complex design, surface quality, ease of use, throughput, material cost, and equipment cost. The reason why we did not take the criteria such as capacity and volume was due to the fact that the company will use 3D printer technology only in the rapid prototyping process in the design of small products. Since the criteria in the study do not have equal weight on decision making, criterion weighting has been made. The criterion with the highest weight in the decision-making process was “accuracy”. Different 3D printing technologies have different levels of accuracy. Due to the fact that 3D printers depend on a large number of parts, the correct production of parts is seen as an important issue (Ye, 2021). The second most influential criterion in the 3D printer decision was determined as the cost of equipment. Ultimately, additive manufacturing technologies require equipment-based investment. In terms of businesses, one of the most common obstacles to owning this technology is equipment costs

(Micińsk et al., 2021; Beliatis et al., 2022). The third most important criterion is surface quality. There are different situations that affect the surface quality of printed products. These can be various effects such as choice of filament, use of support material, and geometry to be printed. Although there are different parameters, most of them may vary depending on the type of technology chosen. In this direction, the product design team has also considered the surface quality as one of the most important criteria. Ultimately, accuracy, equipment cost, and surface quality account for more than half of the 3D printing technology selection decision. In short, these three factors play a decisive role in the technology selection process. The last priority among the seven criteria is the ease of use of technology. Although the ease of use of 3D printers is still a concern, manufacturers today can provide ease of use with advanced technologies. Touch screens, automatic features, and good build surfaces make these printers easy to install and operate (Dwamena, 2021).

In the study, FDM, SLS, and SLA technologies were evaluated as the most suitable technology for rapid prototyping. At this point, there is an important limitation of the study. The 3D printer technologies included in this application include the most well-known average models. For example, printers with SLA technology generally produce more accurately than printers with FDM technology. This information can be seen in Table 4 of the study. However, a low-cost, underdeveloped SLA printer can produce more accurate parts than a high-end FDM printer (Ye, 2021). In other words, according to the level of development of a technology, situations may change according to the less developed type of another technology. The situation assessed here is that those in practice are typical printers.

Technologies have different features, so the printer, which is the best option according to different criteria, may change. The important thing here is to find the most suitable printer, taking into account the criteria weights. As a result of the evaluations, it should be considered more likely that the company in the automobile industry will prefer SLA technology to use in the rapid prototyping process. More specifically, SLA technology is the most appropriate technology when a business cares more about accuracy, equipment cost, and surface quality in rapid prototyping products. However, this result does not show that FDM and SLS technology are not suitable. According to the result, both technologies resulted in a rate of 32% according to the selected criteria. Although FDM and SLS are different technologies, the preferability of the company according to the product design purpose is at the same level.

There is an important limitation of the study. There are three different printer technologies in the study, namely fused deposition modeling (FDM), selective laser sintering (SLS), and stereolithography (SLA). This study highlights the differences and similarities between these three additive manufacturing technologies in line with certain criteria. However, as it is known, each technology has different models according to different development levels. Since this study aims to compare technologies unlike other studies, the research was conducted by taking into account the typical models of technologies. At the same time, the 3D printer manufacturer expert has taken into account the average cost printers that are most used and have the most general features. For this reason, this is the most critical point for the study.

Sensitivity analysis was not performed in the study. The application was completed when the consistency rate of the findings remained at the desired level, as stated in Saaty's (1980) study. However, this situation can be evaluated by other researchers doing research on the relevant subject. The results can be compared by using other multi-criteria decision-making methods for the study. It is a matter of curiosity whether similar findings will be obtained in this direction. Therefore, other researchers may repeat the study to test this.

Finally, different studies for researchers who are interested in the subject will also contribute to the literature. The criteria for moving from this study may vary according to different sectors, which may change the level of importance of the criteria. The possible results of the application in different sectors are also a matter of curiosity. Secondly, other additive manufacturing technologies that can be used in rapid prototyping processes can be included in the study and re-evaluated.

Declarations and Disclosures

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