The International Journal of Advanced Manufacturing Technology (2019) 105:4059–4069
https://doi.org/10.1007/s00170-018-1927-8

ORIGINAL ARTICLE

Advanced 3D printing technologies for the aircraft industry: a fuzzy systematic approach for assessing the critical factors

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Received: 21 January 2018 / Accepted: 15 March 2018 / Published online: 5 April 2018

Abstract
In the aircraft industry, three-dimensional (3D) printing can confer several benefits, such as shortened cycle times, reduced production costs, and lighter part weights. However, some concerns must be addressed for 3D-printing applications to be viable. This paper investigated these concerns by reviewing the current 3D printing practices in the aircraft industry. The literature review identified five factors critical to the applicability of advanced 3D printing technologies to the aircraft industry, and a fuzzy systematic approach was applied to assess the applicability and relative importance of the identified factors, combining fuzzy geometric mean and fuzzy analytical hierarchy process. The findings provide valuable input for countries or regions considering expanding 3D printing applications to their aircraft industries.

Keywords 3D printing · Aircraft industry · Fuzzy geometric mean · Fuzzy analytical hierarchy process

1 Introduction

3D printing is a process that uses computer-aided design (CAD) data to achieve the continuous layered deposition of different shapes to produce 3D objects [39]. Consequently, 3D printed objects can have any geometric shapes and features. Originally, 3D printing referred to the orderly deposition of layers of powdered material through inkjet print heads. Later, the term has taken on a wider range of meanings, and it has been used to refer to various technologies such as extrusion and sintering processes. The technical term "incremental manufacturing" can be used to express this broad meaning. 3D fabrication methods can be categorized into seven types: fused deposition modeling (FDM) [2, 13], laminated object manufacturing [26], digital light processing, stereo lithography (SLA), 3D printing, selective laser sintering (SLS) [6], and selective laser melting [1, 20]. Typical general-purpose 3D printing systems can rapidly produce objects with only a single color. The demands of real-world applications motivated the development of 3D printing technologies that fabricate variously colored products.

This study focused on the application of 3D printing to the aircraft industry. Modern production technologies for aircraft spare parts often involve incremental forming, high-speed cutting, high-energy beam processing, and precise forming. The advantages of these methods include low levels of mechanical pressure, small deformations, and structures with long lifespans. Recently, the production technologies of aircraft have migrated from manual labor processes, semimechanized processes, and mechanized processes to digital control, flexibility, and automation [3].

The applications of 3D printing in the aircraft industry differ from those in other industries in the following aspects:

1. Oligopoly: The aircraft industry is an oligopoly with only a few vendors capable of making airplanes, such as Boeing and Airbus. Many studies have reported that 3D printing can be applied to make the parts of an airplane [8]. In addition, 3D printers are easy to acquire and install. Therefore, the application of 3D printing may contribute to the globalization of the aircraft industry [10].

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2. Project-based production: The construction of an airplane is typically planned and executed as a project [42], so is the printing of 3D objects. Neither is intended for mass production. Therefore, 3D printing is feasible for the aircraft industry.
3. Long cycle times: The project horizon for constructing an airplane is typically long. Therefore, to reduce the cycle time of an airplane part or eliminate the need to assemble some parts is critical. To date, 3D printing has proven effective. However, 3D printing may not be efficient in industries involving mass production [29].
4. The pursuit of lighter products: The lightweight of airplanes reduces the fuel consumption and in turn elevates profitability. Such a phenomenon is due to the environment in which airplanes are operated, but is not that obvious in other industries. There have been sufficient evidences for the capability of 3D printing in making aircraft components with lighter weights [22].

To date, 3D printing has benefitted the aircraft industry with shortened cycle times, reduced production costs, and lighter component weights [22]. In addition, the aviation market demands that spare parts be delivered rapidly. By 3D printing spare parts domestically, the need for transporting spare parts to meet the local demand is eliminated; thereby, the cycle time can be dramatically shortened. However, the following concerns must still be addressed:

1. The aircraft industry is a high-tech industry. Many countries or regions require but lack the capability to manufacture, maintain, or repair aircraft parts on their own; 3D printing provides an opportunity for these countries or regions to gain this capability at low cost in a short time. To such countries or regions, an introduction of the current practice of applying 3D printing to the aircraft industry is required.
2. The application of 3D printing in the aircraft industry is ongoing. Some efforts should be made to clarify which related topics are more critical, feasible, or useful.
3. Rapid advances in 3D printing technologies have been observed in the recent years. As a result, the previous reviews on similar topics may become out-of-date. For example, the past efforts and reviews, such as Marks [24] and Moon et al. [25], often focused on the application of 3D printing to making small, unmanned aerial vehicles. Recently, the focus has gradually switched to making lightweight aircraft parts using 3D printing, e.g., Helsel [21] and Huang et al. [22]. Such advances should be summarized with an updated review. In addition, there have been significant advances in computer and internet technologies in the recent years [10], which facilitates the transmission of 3D models and know-how. This topic has rarely been covered in the past reviews.

To address these concerns, this study reviewed the current applications of 3D printing in the aircraft industry. The review identified various critical factors regarding the applicability of advanced 3D printing technologies to the aircraft industry. A fuzzy systematic approach was applied to assess the applicability based on these identified factors. The applied approach combined fuzzy geometric mean (FGM) and fuzzy analytical hierarchy process (FAHP), to aggregate multiple expert opinions on the relative importance of the identified factors and derive the weight for each. These weights provide valuable input to manage activities related to the critical factors under limited resources.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature, focusing first on existing applications of 3D printing technologies to various industries, and then existing research and practices of applying 3D printing in the aircraft industry. Various factors critical to the applicability of advanced 3D printing technologies to the aircraft industry were identified from the review. Section 3 details the fuzzy systematic approach to assess the applicability of advanced 3D printing technologies to the aircraft industry based on the identified critical factors, and discusses the outcomes. Finally, Section 4 presents concluding remarks.

2 Literature review

2.1 Application of 3D printing in various industries

3D printing has been applied in numerous industries. For example, in the automotive manufacturing industry, automotive makers have applied 3D printing technologies to prototyping or production in low quantities. For the past few years, all large automotive makers have expedited novel applications of 3D printing technologies to final inspection and design validation. For example, 3D printing is used for testing the functional spare parts of vehicles, engines, and platforms [23]. Annually, more than 100,000 parts and additional molds are prototyped or manufactured using 3D printing by automotive makers [5]. In the health care industry, 3D printing technologies have been widely applied to products such as hearing aids, artificial ears, prostheses, rehabilitation aids, orthopedic surgery personalized guide plates, artificial joints, and personalized dental implants [38]. 3D printing technologies applied to the design and manufacturing of these products can satisfy personalized demand. When porous titanium structures are used for metal printing, medical products are lighter, are more ergonomic, and have higher performance. These can overcome the limitations of the traditional manufacturing processes. Titanium has found extensive applications in various industries such as aerospace, chemical, and biomedical industries due to properties including lightweight, high specific strength, excellent chemical resistance, and biocompatibility [43]. In the biomedical industry, titanium is used to create implants because of its load bearing and biocompatibility [30], while in the aviation industry, the resistance to corrosion and lightweight of titanium are emphasized [19]. Titanium is about 45% lighter than steel [15]. The replacement of steel with titanium has reduced the weight of a 777 airplane by 5800 pounds [33]. A lighter weight also reduces the required fuels and carbon emission, which further promoted the usage of titanium in aircraft. In addition, titanium is twice as strong as aluminum that is frequently used to build the overall structure of an airplane [15, 33].

In addition, the traditional manufacturing processes are relatively complex, have long cycle times, and are difficult to maintain precision. The applications of 3D printing technologies have overcome these problems to reduce the manufacturing costs and shorten cycle times [30]. In the construction industry, 3D printing technologies have been applied to build simple, affordable, and rapidly fabricated models. Detailed models can be directly made from the data generated by 3D CAD, building information modeling, or architects. The use of 3D printing technologies also motivates the innovation and communication during the working processes. Recently, some forward-thinking architects have been seeking 3D printing technologies as a direct method of construction [9].

2.2 3D printing applications for the aircraft industry

2.2.1 Application scope

3D printing can be applied to rapid prototyping, rapid tooling, and/or rapid manufacturing. There are differences among the three applications. Rapid prototyping is to quickly produce the prototype of a part from its 3D CAD file [27] at the product design and/or development stage. In contrast, rapid tooling and rapid manufacturing belong to the manufacturing stage. Rapid tooling is to quickly make a tool, usually for injection molding or die casting operations, that can be used to form a variety of parts [14], while rapid manufacturing aims to make an end product using additive manufacturing technologies [17]. The applications of 3D printing in the aircraft industry cover the three categories (see Table 1).

Table 1 The classification of 3D printing applications in the aircraft industry

Category	Applications
Rapid prototyping	• To test the functional spare parts of vehicles, engines, or platforms [23] • To generate the prototypes of aircraft parts [36] • To evaluate the machinability of molds made with silicon matrixes instead of traditional metal matrices [8]
Rapid tooling	• To make the molding model of turbocharger blades and impellers [8] • To mimic natural structures in making aircraft parts [18] • To identify the truss lattice with optimal elastic performance for deployable unmanned aerial vehicle wing design [25]
Rapid manufacturing	• To make spare parts for aircraft maintenance [8, 22, 41] • To make an entire drone or unmanned aerial vehicle [24] • To create a global supply chain of spare parts [10]

Current 3D printing practices in the aircraft industry were observed from the following perspectives: adoption by major aircraft manufacturers, market for 3D printing applications, materials used in the existing 3D printing applications, 3D printing technology adopted in the existing applications, and 3D printing applications for aircraft maintenance.

2.2.2 Adoption by major aircraft manufacturers

The adoption of 3D printing by major aircraft manufacturers confirms the usefulness and prevalence of 3D printing applications in the aircraft industry. Boeing has 3D printed numerous airplane components, including 300 different types of parts, more than 20,000 pieces, and 10 different models of aircrafts.

Airbus believed that 3D printing technologies can produce all the parts of an A350 airplane, and the weight can be reduced to approximately 1 ton. The weight of an A350 is 192 tons. Currently, an A350 has over 1000 parts that can be 3D printed with ULTEM 9085 resin using FDM, i.e., resin is melted and extruded layer by layer until the entire part is fabricated. So far, the application of 3D printing has reduced the weight of an airplane by about 20% [22]. Therefore, the target of A350 is challenging. Both engine parts and internal cabin parts are typical products of 3D printing technologies. Furthermore, the currently available 3D printing technology can make all parts required to construct an aircraft that meets high-quality standards.

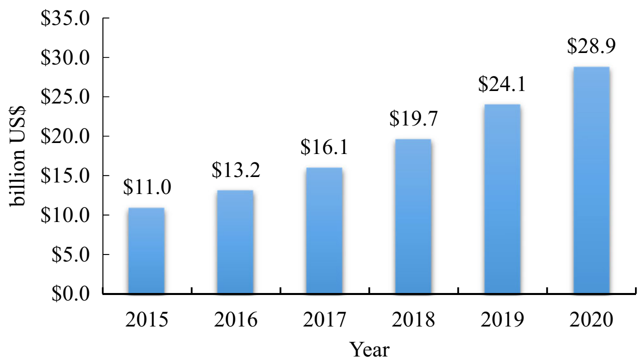

Fig. 1. 2015–2020 3D printing markets

General Electric (GE) proposed the first metal fuel nozzle to be made by 3D printing [12]. The fuel nozzle is installed in Leap-1A engines for the A320neo (Airbus). It is expected that by 2020, 40,000 fuel nozzles will be 3D printed. GE also used 3D printing to make advanced turboprop engines for Denali single-engine airplanes. This application eliminated the need for 845 parts; the related machines; and procurement, installation, inspection, and control efforts. The weight of the engines was also considerably reduced.

2.2.3 Market for 3D printing applications

Figure 1 provides an estimate of the global market for 3D printing applications from 2015 to 2020. In 2016, the global revenues were estimated at US$13.2 billion. Whereas software and services currently contribute a small share of the revenues, it was estimated that within 4 years, the proportions of hardware and materials will decline to half of the total revenues, and the share of software and relevant services will dramatically increase. The markets for 3D printing software, services, and spare parts are expected to nearly triple [34].

In 2016, 3.7 billion people boarded aircraft flights globally. Therefore, Boeing predicted that in the next 20 years, 38,050 new airplanes will be required for passengers and cargo, and that the costs will amount to US$5.6 trillion.

2.2.4 Materials used in existing 3D printing applications

Traditional aircraft parts are made with aluminum alloys. A trend is to use other materials instead such as titanium alloys, light alloy structures, and composite structures. Both aluminum and titanium alloys are used to make 3D printed aircraft parts. For example, Grünberger and Domröse [19] built titanium parts by melting fine metal powder with a laser beam. This technology is called direct metal laser sintering (DMLS). Moreover, many attempts have been made to 3D print airplane parts or their molding models with new alloys. For example, to 3D print the molding models of turbocharger blades and impellers, Budzik [8] used silicon matrixes instead of traditional metal matrices, which enhanced their machinability. Airbus has used a new alloy called Scalmalloy to 3D print the partition between the seating area and galley on an airplane. This is the largest part that has ever been 3D printed, and it needs to be very strong, which typically makes it heavy. However, 3D printing the part reduced 45% of the weight [25], which consequently reduced fuel consumption and CO_2 emission. Moon et al. [25] used a polypropylene-like photopolymer called Objet DurusWhite RGD430 to build the wings of an unmanned aerial vehicle (UAV).

The raw materials used in 3D printing are often more expensive than those used in conventional manufacturing [37]. Nevertheless, through more precise machining, 3D printing can use less materials than conventional manufacturing, dramatically reducing the volume of expensive raw materials required by aviation spare parts [8]. In addition, it is expected the unit cost of raw materials for 3D printing will continue to decline, making 3D printing more and more cost-effective.

2.2.5 3D printing technology adopted in existing applications

In the past, the production of a single engine required the manipulation of 300 independent parts crossing over 50 sets of equipment. A single-engine design required 60 industrial designers using 40 types of different industrial design data systems. By contrast, 3D printing only requires a set of design data, eight engineers, and a 3D printer. All steps are controlled by the GE Predix information system. 3D printing an engine also promotes its safety.

Numerous 3D printing strategies have been applied in the aircraft industry. Budzik [8] used SLA technology to 3D print the molding models of turbocharger blades and impellers. Boeing has used SLS technologies to produce some thermoplastic aircraft components of Boeing 737 and 747 airplanes [40]. DMLS technology was proposed for making aircraft parts with titanium alloys [19] or Scalmalloy [28]. 3D printed airplane bodies can eliminate 55% of the weight of traditional airplane bodies, and they are also stronger. Furthermore, they can be built in a brand new production process that reduces energy consumption by 90% and raw material consumption by 95% [41].

2.2.6 3D printing applications for aircraft maintenance

3D printing has been widely applied to prepare the spare parts of some aircraft components, among which the engine is particularly critical. The spare parts of engines are easily damaged, which is especially troublesome for imported spare parts that require regular replacement.

Table 2 Companies that use 3D printing technologies

Company name	Name of spare parts	Remark
Rolls-Royce Group plc	Metal spare parts of jet engines	Trial production since 2013
Siemens	Metal spare parts of gas turbines	Applicable since 2014
Honeywell	Heat exchangers and metal stents	Trial production since 2013
MTU Aero Engines AG	Blade components of high press guides with complex shapes	Applicable since 2018
General Electric Company	Spare parts of the fuel nozzles of engines in Boeing 747 and Airbus 320	Applicable since 2016

3D printing is a solution to the procurement of such spare parts. Since 2013, increasing numbers of the spare parts of engines have been 3D printed, as shown in Table 2. Siemens was the first firm to establish a global business organization dedicated to making metal spare parts through 3D printing. For companies that demand small quantities of spare parts for engine maintenance, 3D printing technologies can lower production costs and shorten maintenance cycles.

3 The fuzzy systematic approach

The review showed that the following five factors are critical to the applicability of advanced 3D printing technologies to the aircraft industry:

1. The cost-effectiveness,
2. The capability to meet special demands, including emergency demands, vanishing sources, and special parts,
3. The printability of aircraft parts,
4. The lack of aircraft part manufacturing technologies, and
5. The size of the local aircraft maintenance market.

The references that highlighted the importance of these critical factors were summarized in Table 3. The relative importance of these critical factors is unclear. Therefore, we used a systematic fuzzy approach to establish this ranking. The fuzzy approach included FGM and FAHP, as described below.

Table 3 The references that highlighted the importance of the critical factors

Critical factor	References
The cost-effectiveness	Budzik [8], Moon et al. [25], Helsel [21], Weller et al. [40]
The capability to meet special demands	Williams [42], Moon et al. [25], Huang et al. [22], Welte [41], Pinkham [28]
The printability of aircraft parts	Smith [33], Budzik [8], Marks [24], Moon et al. [25], Helsel [21], Weller et al. [40], Welte [41], Pinkham [28]
The lack of aircraft part manufacturing technologies	Budzik [8], Marks [24]
The size of the local aircraft maintenance market	Weller et al. [40], Huang et al. [22], Welte [41]

3.1 FGM

Several domain experts were invited to pairwise compare the importance the critical factors. To be compatible with the subsequent FAHP method, only positive comparisons were accepted, i.e., a critical factor is more important than another to some degree. To aggregate the comparisons, FGM was considered to be more suitable than fuzzy weighted average (FWA) [7]:

$$\tilde{r}_{ij} = \sqrt[P]{\prod_{p=1}^{P} \tilde{r}_{ijp}}, \tag{1}$$

where $i,j = 1,\ldots, n$; $i \neq j$; $\tilde{r}_{ij}$ is the aggregation result of the relative importance of critical factor i over critical factor j; $\tilde{r}_{ijp}$ = 1–9 is the comparison result by domain expert p. Without loss of generality, $\tilde{r}_{ijp}$ is expressed as a triangular fuzzy number (TFN):

$$\tilde{r}_{ijp} = \left(r_{ijp1},\ r_{ijp2},\ r_{ijp3}\right) \tag{2}$$

where $\tilde{r}_{ijp}$ are chosen from the following values [16, 35] (see Fig. 2):

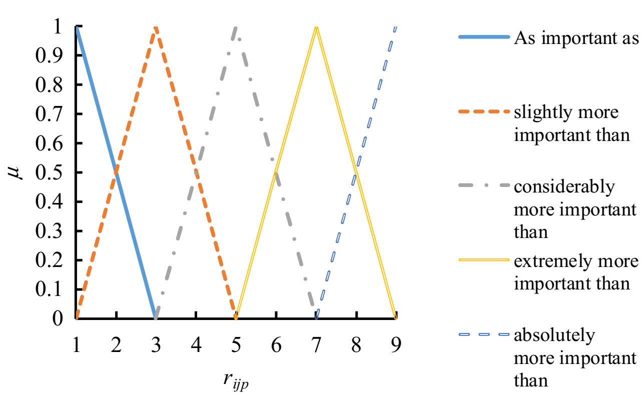

Fig. 2 The used linguistic terms

Table 4 Pairwise comparison by domain experts

p	Pairwise comparison results
1	(i) "Cost-effectiveness" is slightly more important than "capability to meet special demand." (ii) "Printability of aircraft parts" is considerably more important than "cost-effectiveness." (iii) "Cost-effectiveness" is considerably more important than "lack of aircraft part manufacturing technologies." (iv) "Cost-effectiveness" is slightly more important than "size of the local aircraft maintenance market." (v) "Printability of aircraft parts" is considerably more important than "capability to meet special demand." (vi) "Capability to meet special demand" is considerably more important than "lack of aircraft part manufacturing technologies." (vii) "Capability to meet special demand" is slightly more important than "size of the local aircraft maintenance market." (viii) "Printability of aircraft parts" is extremely more important than "lack of aircraft part manufacturing technologies." (ix) "Printability of aircraft parts" is considerably more important than "size of the local aircraft maintenance market." (x) "Size of the local aircraft maintenance market" is slightly more important than "lack of aircraft part manufacturing technologies."
2	(i) "Capability to meet special demand" is extremely more important than "cost-effectiveness." (ii) "Printability of aircraft parts" is considerably more important than "cost-effectiveness." (iii) "Lack of aircraft part manufacturing technologies" is extremely more important than "cost-effectiveness." (iv) "Cost-effectiveness" is considerably more important than "size of the local aircraft maintenance market." (v) "Printability of aircraft parts" is considerably more important than "capability to meet special demand." (vi) "Capability to meet special demand" is extremely more important than "lack of aircraft part manufacturing technologies." (vii) "Capability to meet special demand" is extremely more important than "size of the local aircraft maintenance market." (viii) "Printability of aircraft parts" is considerably more important than "lack of aircraft part manufacturing technologies." (ix) "Printability of aircraft parts" is extremely more important than "size of the local aircraft maintenance market." (x) "Size of the local aircraft maintenance market" is considerably more important than "lack of aircraft part manufacturing technologies."
3	(i) "Capability to meet special demand" is extremely more important than "cost-effectiveness." (ii) "Printability of aircraft parts" is extremely more important than "cost-effectiveness." (iii) "Lack of aircraft part manufacturing technologies" is extremely more important than "cost-effectiveness." (iv) "Cost-effectiveness" is extremely more important than "size of the local aircraft maintenance market." (v) "Printability of aircraft parts" is extremely more important than "capability to meet special demand." (vi) "Capability to meet special demand" is extremely more important than "lack of aircraft part manufacturing technologies." (vii) "Capability to meet special demand" is extremely more important than "size of the local aircraft maintenance market." (viii) "Printability of aircraft parts" is extremely more important than "lack of aircraft part manufacturing technologies." (ix) "Printability of aircraft parts" is extremely more important than "size of the local aircraft maintenance market." (x) "Lack of aircraft part manufacturing technologies" is extremely more important than "size of the local aircraft maintenance market."
4	(i) "Cost-effectiveness" is extremely more important than "capability to meet special demand." (ii) "Printability of aircraft parts" is slightly more important than "cost-effectiveness." (iii) "Cost-effectiveness" is slightly more important than "lack of aircraft part manufacturing technologies." (iv) "Cost-effectiveness" is considerably more important than "size of the local aircraft maintenance market." (v) "Printability of aircraft parts" is considerably more important than "capability to meet special demand." (vi) "Capability to meet special demand" is extremely more important than "lack of aircraft part manufacturing technologies." (vii) "Capability to meet special demand" is considerably more important than "size of the local aircraft maintenance market." (viii) "Printability of aircraft parts" is slightly more important than "lack of aircraft part manufacturing technologies." (ix) "Printability of aircraft parts" is slightly more important than "size of the local aircraft maintenance market." (x) "Size of the local aircraft maintenance market" is extremely more important than "lack of aircraft part manufacturing technologies."
5	(i) "Capability to meet special demand" is slightly more important than "cost-effectiveness." (ii) "Printability of aircraft parts" is as important as "cost-effectiveness." (iii) "Lack of aircraft part manufacturing technologies" is considerably more important than "cost-effectiveness." (iv) "Size of the local aircraft maintenance market" is extremely more important than "cost-effectiveness." (v) "Printability of aircraft parts" is slightly more important than "capability to meet special demand." (vi) "Lack of aircraft part manufacturing technologies" is as important as "capability to meet special demand." (vii) "Size of the local aircraft maintenance market" is slightly more important than "capability to meet special demand." (viii) "Lack of aircraft part manufacturing technologies" is slightly more important than "printability of aircraft parts." (ix) "Size of the local aircraft maintenance market" is as important as "printability of aircraft parts." (x) "Size of the local aircraft maintenance market" is as important as "lack of aircraft part manufacturing technologies."

As important as $\tilde{r}_{ijp} = (1, 3)$,
Slightly more important than $\tilde{r}_{ijp} = (1, 3, 5)$,
Considerably more important than $\tilde{r}_{ijp} = (3, 5, 7)$,
Extremely more important than $\tilde{r}_{ijp} = (5, 7, 9)$, and
Absolutely more important than $\tilde{r}_{ijp} = (7, 9)$.

We define

$$\tilde{r}_{jip} = \frac{1}{\tilde{r}_{ijp}}. \quad (3)$$

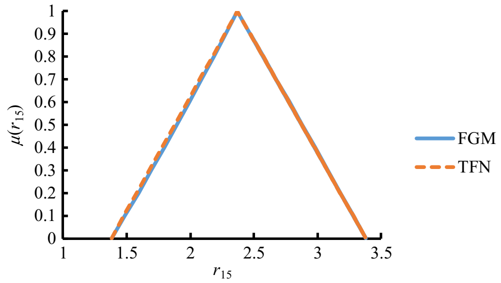

Fig. 3 The aggregated result of the relative importance ($\tilde{r}_{15}$ as an example)

Property 1.

$\tilde{r}_{ij}$ determined using Eq. (1) may not be a TFN.

α-cut operations can be applied to solve for $\tilde{r}_{ij}$:

$$r_{ij}^{(\alpha)} = \left[\min \sqrt[P]{\prod_{p=1}^{P} r_{ijp}^{(\alpha)}},\ \max \sqrt[P]{\prod_{p=1}^{P} r_{ijp}^{(\alpha)}}\right] = \left[\sqrt[P]{\prod_{p=1}^{P} \min r_{ijp}^{(\alpha)}},\ \sqrt[P]{\prod_{p=1}^{P} \max r_{ijp}^{(\alpha)}}\right] \tag{4}$$

where $r_{ij}^{(\alpha)}$ and $r_{ijp}^{(\alpha)}$ are the α cuts of $\tilde{r}_{ij}$ and $\tilde{r}_{ijp}$, respectively. To enhance the practicability and facilitate the subsequent operations, $\tilde{r}_{ij}$ can be approximated with a TFN as

$$\tilde{r}_{ij} \cong \left(\min r_{ij}^{(0)},\ r_{ij}^{(1)},\ \max r_{ij}^{(0)}\right). \tag{5}$$

3.2 FAHP

FAHP has been extensively applied to various fields for multiple attribute decision-making (MADM). For example, Chen and Yang [11] applied constrained FAHP to supplier selection, in which the values of weights were derived using the extent analysis technique. Based on the weights, the fuzzy technique for order preference by similarity to an ideal solution (FTOPSIS) was applied to rank the alternatives. Ashour and Kremer [4] applied FAHP to compare the relative importance of the five attributes of a patient: the chief complaint, age, gender, the pain level, and vital signs. Then, the multi-attribute utility theory (MAUT) was applied to rank patients according to the derived weights.

Table 5 Approximating TFNs

$\tilde{r}_{ij}$	TFN
$\tilde{r}_{15}$	(1.38, 2.37, 3.38)
$\tilde{r}_{21}$	(0.89, 1.48, 2.41)
$\tilde{r}_{24}$	(2.63, 4.43, 5.52)
$\tilde{r}_{25}$	(1.72, 3.00, 4.90)
$\tilde{r}_{31}$	(2.14, 3.50, 5.81)
$\tilde{r}_{32}$	(2.67, 4.83, 6.88)
$\tilde{r}_{34}$	(2.14, 3.33, 5.24)
$\tilde{r}_{35}$	(2.63, 4.43, 5.52)
$\tilde{r}_{41}$	(1.16, 1.75, 2.85)
$\tilde{r}_{54}$	(1.11, 1.72, 2.85)

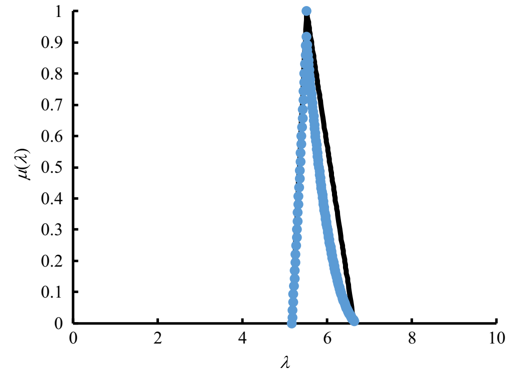

Fig. 4 The fuzzy maximal eigenvalue

In the proposed methodology, FAHP was subsequently applied to derive the weight of each critical factor. Let $\tilde{A} = (\tilde{a}_{ij})$ be the (fuzzy) pairwise comparison matrix

$$\tilde{a}_{ij} = \begin{cases} 1 & if \quad i = j \\ \tilde{r}_{ij} & if \quad i \neq j \text{ and } \tilde{r}_{ij} \text{ exists} \\ \frac{1}{\tilde{r}_{ji}} & otherwise \end{cases}. \tag{6}$$

Then, the fuzzy maximal eigenvalue ($\tilde{\lambda}$) and the corresponding fuzzy eigenvector ($\tilde{x}$) of $\tilde{A}$ are

$$\left(\tilde{A}(-)\tilde{\lambda}I\right)(\times)\tilde{x} = 0, \tag{7}$$

where (−) denotes fuzzy subtraction. The fuzzy consistency ratio ($\tilde{C}$) can be expressed as

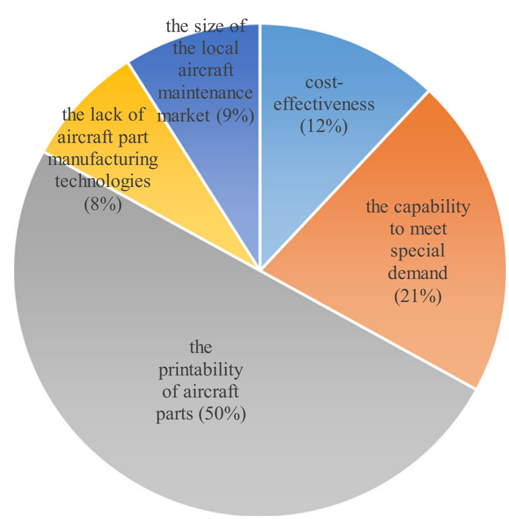

Fig. 5 The optimal budget allocation

$$\tilde{C} = \frac{\frac{\tilde{\lambda}-n}{n-1}}{R}, \tag{8}$$

where R is the random index [32], and $\tilde{C} \leq 0.1$.

Property 2.

1. Since $\tilde{r}_{ij}$ and $\tilde{a}_{ij}$ are not TFNs, $\tilde{\lambda}$ and $\tilde{x}$ are not TFNs.
2. Even if $\tilde{r}_{ij}$ is approximated with a TFN, $\tilde{\lambda}$ and $\tilde{x}$ are still not, but can be approximated with, TFNs.

3.2.1 Fuzzy extent analysis

In previous work, $\tilde{\lambda}$ and $\tilde{x}$ were estimated by applying the fuzzy arithmetic mean, the fuzzy geometric mean, α-cut operations, or the extent analysis technique [11, 31]. In the proposed methodology, the extent analysis technique was applied.

Let the fuzzy synthetic extent be indicated with $\tilde{s}_i = (s_{li}, \ s_{mi}, \ s_{ui})$ where

$$s_{mi} = \frac{\sum_{j=1}^{n} a_{ij2}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij2}} \tag{9}$$

s_{li} can be derived by constructing a matrix $B_i = (b_{kj})$ in which

$$b_{kj} = \begin{cases} 1 & \text{if} \quad k = j \\ a_{ij1} & \text{if} \quad k = i, j \neq i \\ \left\{ x \middle| y = \max\left(x + \frac{1}{x}\right), \ \forall x \in \left[a_{kj1}, \ a_{kj3}\right] \right\} & \text{if} \quad k \neq i, j \neq i, j > k \\ \frac{1}{b_{jk}} & \text{otherwise} \end{cases} \tag{10}$$

Then

$$s_{li} = \frac{\sum_{j=1}^{n} b_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} b_{kj}} \tag{11}$$

In a similar way, s_{ui} is derived by constructing a matrix $C_i = (c_{kj})$ in which

$$c_{kj} = \begin{cases} 1 & \text{if} \quad k = j \\ a_{ij3} & \text{if} \quad k = i, j \neq i \\ \left\{ x \middle| y = \max\left(x + \frac{1}{x}\right), \ \forall x \in \left[a_{kj1}, \ a_{kj3}\right] \right\} & \text{if} \quad k \neq i, j \neq i, j > k \\ \frac{1}{c_{jk}} & \text{otherwise} \end{cases} \tag{12}$$

Then

$$s_{ui} = \frac{\sum_{j=1}^{n} c_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} c_{kj}} \tag{13}$$

The fuzzy synthetic extents can be used to derive the relative importance of critical factors. First, the possibility of a fuzzy synthetic extent greater than another, $\tilde{s}_2 \geq \tilde{s}_1$, is defined as

$$\begin{aligned} \upsilon\left(\tilde{s}_2 \geq \tilde{s}_1\right) &= \sup_{y \geq x}\left(\min\left(\mu_{\tilde{s}_1}(x), \ \mu_{\tilde{s}_2}(y)\right)\right) \\ &= \operatorname{hgt}\left(\tilde{s}_1 \cap \tilde{s}_2\right) \\ &= \begin{cases} 1 & \text{if} \quad s_{2m} \geq s_{1m} \\ 0 & \text{if} \quad s_{1l} \geq s_{2u} \\ \frac{s_{1l}-s_{2u}}{(s_{2m}-s_{2u})-(s_{1m}-s_{1l})} & \text{otherwise} \end{cases} \end{aligned} \tag{14}$$

Letting

$$\delta\left(\tilde{s}_i\right) = \min_j \upsilon\left(\tilde{s}_i \geq \tilde{s}_j\right) \quad (15)$$

Then, the relative weight vector $W = (w_i)$ can be derived as

$$w_i = \frac{\delta\left(\tilde{s}_i\right)}{\sum_{j=1}^{n} \delta\left(\tilde{s}_j\right)} \quad (16)$$

3.3 Results

Five domain experts (including a professor researching 3D printing management, three managers from aviation companies, and an assistant professor of aviation mechanical engineering) were asked to perform pairwise comparisons, as summarized in Table 4.

Figure 3 shows the aggregated result of the relative importance, with $\tilde{r}_{15}$ as an example. $\tilde{r}_{15}$ is the average of the assessments by the five experts and represents the relative importance of "the cost-effectiveness" over "the size of the local aircraft maintenance market." A TFN seemed to be a good fit, and the approximate $\tilde{r}_{ij}$'s are summarized in Table 5. Each TFN in Table 5 is obtained by retaining only the minimum, core, and maximum of the $\tilde{r}_{ij}$.

Thus, the fuzzy pairwise comparison matrix $\tilde{A}$ is

$$\tilde{A} = \begin{bmatrix} 1 & \frac{1}{(0.89,\ 1.48,\ 2.41)} & \frac{1}{(2.14,\ 3.50,\ 5.81)} & \frac{1}{(1.16,\ 1.75,\ 2.85)} & (1.38,\ 2.37,\ 3.38) \\ (0.89,\ 1.48,\ 2.41) & 1 & \frac{1}{(2.67,\ 4.83,\ 6.88)} & (2.63,\ 4.43,\ 5.52) & (1.72,\ 3.00,\ 4.90) \\ (2.14,\ 3.50,\ 5.81) & (2.67,\ 4.83,\ 6.88) & 1 & (2.14,\ 4.43,\ 5.52) & (2.63,\ 4.43,\ 5.52) \\ (1.16,\ 1.75,\ 2.85) & \frac{1}{(2.63,\ 4.43,\ 5.52)} & \frac{1}{(2.14,\ 4.43,\ 5.52)} & 1 & \frac{1}{(1.11,\ 1.72,\ 2.85)} \\ \frac{1}{(1.38,\ 2.37,\ 3.38)} & \frac{1}{(1.72,\ 3.00,\ 4.90)} & \frac{1}{(2.63,\ 4.43,\ 5.52)} & (1.11,\ 1.72,\ 2.85) & 1 \end{bmatrix} \quad (17)$$

The maximal eigenvalue ($\tilde{\lambda}$) of $\tilde{A}$ was derived using α-cut operations. The result is shown in Fig. 4.

After approximated $\tilde{\lambda}$ with a TFN,

$$\tilde{\lambda} \cong (5.17,\ 5.52,\ 6.64) \quad (18)$$

The related weight of the critical factors was derived using the fuzzy extent analysis technique as

$$W = \begin{bmatrix} 0.12 \\ 0.21 \\ 0.50 \\ 0.08 \\ 0.09 \end{bmatrix} \quad (19)$$

Therefore, the following conclusions can be drawn:

1. The printability of aircraft parts was considered the most important factor, followed by the capability to meet special demand, and the cost-effectiveness.
2. If the government of a region is considering allocating its budget on activities supporting the realization of the critical factors, the budget should be divided as shown in Fig. 5.
3. The fuzzy consistency index is

$$\tilde{C} = (0.04,\ 0.12,\ 0.37) \quad (20)$$

which shows some lack of consensus. However, this was not unexpected, since 3D printing applications for the aircraft industry are in their infancy.

4 Conclusions

Several types of spare parts are required by an airline. 3D printing technologies have been applied to make small quantities of some spare aircraft parts. These technologies offer advantages including short production cycles, low production costs, higher strengths, and low product weights. Within the next 10 years, sectional airplane bodies could be 3D printed. One might hope that by 2025, whole airplane bodies could be 3D printed.

Numerous airlines worldwide are adopting 3D printing technology, not only to enable innovative airplane designs but also to expedite the manufacturing and maintenance of airplanes. The spare parts made by 3D printing technologies could be easily reinstalled or redesigned without the necessity to redesign new tools. This paper reviews the current practices of 3D printing applications to the aircraft industry. Five factors critical to the application of 3D printing for the aircraft industry were identified from the survey. A fuzzy systematic approach was applied to assess the applicability of advanced 3D printing technologies to the aircraft industry based on the critical factors, and compare their relative importance. The following results were obtained.

1. The three most important critical factors were printability of aircraft parts, capability to meet special demand, and the cost-effectiveness.
2. Accordingly, approximately 50, 21, and 12% of the budget should be allocated to the realization of these three critical factors, respectively.

In sum, the major airplane makers are taking advantage of 3D printing to enhance their cost-effectiveness in a variety of ways: using new materials to make parts with lighter weights to save fuels, thinking of new ways of assembling parts that enable new designs, eliminating the need to transport spare parts from overseas, eliminating the need to acquire and install dedicated equipment, and enjoying the easiness to disseminate and acquire the required expertise. It is also expected that other smaller airplane makers will follow soon.

The contribution of this study resides in the systematic discussion of 3D printing applications to the aircraft industry. This study not only updated the reviews by mentioning the recent advances in this field, but also found out factors that were critical to such advances by applying a fuzzy systematic approach. The results provide valuable input for countries or regions considering expanding 3D printing applications to their aircraft industries.

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