

A Multi-Criteria Decision Analysis Approach for Managing End-of-Life Options of 3D Printing Thermoplastic

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Abstract

The increasing use of 3D printing technology, particularly with thermoplastic materials, emphasizes the imperative for a meticulously devised strategy to address sustainability concerns at the end of the product's life cycle. This study presents a customized Multi-Criteria Decision Analysis (MCDA) approach designed to navigate the intricate factors that affect the sustainable management of thermoplastic waste generated by 3D printing techniques. This framework provides decision-makers with a methodical paradigm to evaluate and prioritize end-of-life (EOL) modalities. It incorporates a wide range of variables, including resource consumption, environmental impact, economic implications, and statutory requirements. Based on the Analytic Hierarchy Process (AHP), the results of the algorithm clearly indicate that recycling is the best EOL option for the thermoplastic category studied in this analysis compared to other techniques. The utilization of MCDA enables stakeholders to make decisions that not only improve sustainability results but also drive innovation and efficiency within the 3D printing ecosystem.

1. Introduction

The extensive implementation of 3D printing technology has fundamentally revolutionized production processes, providing unparalleled levels of flexibility, efficiency, and versatility across many industries. Thermoplastics have become a popular choice in additive manufacturing (AM) due to their versatility, cost-effectiveness, and wide range of applications [1], [2]. Nevertheless, the swift growth of thermoplastic 3D printing gives rise to substantial apprehensions regarding waste management, environmental consequences, and resource exhaustion. To secure the sustainable long-term utilization of 3D printing technology, it is crucial for us to tackle these difficulties. We must aim to strike a balance between innovation and responsible stewardship of our planet's resources. A sustainability evaluation method was employed to identify the critical issues that need further improvement to achieve sustainability [3].

Furthermore, plastic has consistently been the predominant material utilized in various industries for 3D printing purposes [4]. Plastic is consistently favored as a material for 3D printing due to its multiple beneficial characteristics, including flexibility, stiffness, smoothness, and a wide range of color options [4], [5]. The development of AM [6] has revolutionized the prototyping and production industries, replacing time-consuming and expensive techniques like molding, shaping, and machining. 3D printing is commonly utilized to fabricate prototypes before the production of final products, mostly due to its cost-effectiveness and time efficiency. The process of constructing an object or component through the utilization of 3D printing is highly straightforward and convenient [7], [8].

Recently, there has been a greater increase in the production of products than was projected. The production of goods will rise in tandem with the worldwide population. Production companies place a high emphasis on improving product design, manufacturing procedures, and advertising approaches in order to facilitate the development of superior products [9]. Although plastic goods are highly functional, they pose numerous environmental hazards. The inadequate infrastructure and limited recycling choices often result in the disposal of products in landfills or the ocean, causing substantial environmental pollution. The environmental impact of the manufacturing process is directly proportional to the level of production increase [10]. For several decades, there has been a steady rise in trash generation due to unsustainable consumption and production practices [11].

Solid waste management is a world concern today. The quantity of solid waste deposited in landfills has escalated due to individuals' limited alternatives and awareness regarding the appropriate disposal methods for their waste once a product has reached its point of obsolescence. In contemporary society, individuals frequently discard functional or defective items without possessing the knowledge on how to appropriately dispose of waste. There are numerous methods available for manufacturers to determine how to dispose of end-of-life (EOL) products. Therefore, this study aims to address the issue of determining the EOL of a product, with a specific focus on 3D printing products as the subject of investigation. Several approaches have been developed for decision analysis addressing solid waste related to 3D printing.

Previous research has investigated many methods for addressing EOL concerns in 3D printing. These methods include recycling, material recovery, biodegradation, and the development of alternative materials [12], [13], [14], [15]. Nevertheless, only a limited number of frameworks offer a thorough and organized approach to assess and rank these solutions according to various criteria. Multi-Criteria Decision Analysis (MCDA) is a method that can address this issue by providing a systematic approach to decision-making. It takes into account many objectives, stakeholders, and limitations, making it a viable solution [13].

Hence, this study specifically examined the process of materials extrusion in 3D printing technology. Thermoplastic filaments are the primary materials used in these systems. Various thermoplastics, including Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and Polyether Ether Ketone (PEEK), are commonly utilized as foundation materials in 3D printing technology. These three materials are the commonly used thermoplastic materials in 3D printing [16]. Every material in 3D printing has a distinct purpose.

1.1 End-of-Life (EOL) Options

There are numerous EOL options for products that have reached their EOL. The EOL of a product is the point at which it stops to satisfy its original buyer or user. This often occurs when a newer model or substitute product enters the market, making the current model irrelevant or less attractive. All product materials have different options for product EOL. Prior to making a decision, experts ought to engage in a discussion regarding the various types of EOL options that the preceding author has outlined as follows:

- i. In secondary recycling, a material is transformed into a low-value product, for instance, rubber of high quality for industry is transformed into rubber of general grade [17].
- ii. A component is reused again with its original function (direct use) or with another application (indirect use). For example, reusing the same milk bottle or turning it into a flower vase [18].
- iii. Waste product is dumped into the landfill [19].
- iv. Some materials are incinerated to produce heat and electricity [20].
- v. A material is recycled into a form that can be used in the same way or to create another high-value product in primary recycling. A conveyor belt or remolded car tyre are two examples of how a tyre can be recycled [21].

Manufacturers mitigate the impact of product disposal by proactively incorporating considerations for these consequences throughout the development of concepts and designs. Furthermore, several previous studies have compiled data on the EOL status of numerous products through the use of diverse MCDA methods. These studies demonstrate the effectiveness of MCDA methods in evaluating EOL treatment options for various products, considering economic, environmental, and social factors to promote sustainability. The breakdown of the key findings from each study is listed in Table 1.

Table 1 Summary of methodology for determination of product EOL

Reference	Key Findings
[12]	Developed an MCDA methodology, specifically the Analytic Hierarchy Process (AHP) to select the optimal EOL treatment option for products, considering user preferences and the performance of competing EOL options. Their case study on the "Haier Dry Spray Iron" revealed that 56% of the parts prioritized recycling, while 40% of the product weight favored remanufacturing.
[13]	Utilized Multi-Attribute Value Theory (MAVT) to assess the sustainability of EOL alternatives for waste plastics, focusing on economic, environmental, and social criteria. They found that economic assessment criteria carried the most weight (42%), followed by environmental (34%) and social (23%) criteria. Recycling was identified as the most suitable option compared to landfill and incineration, with variations depending on the weight assigned to environmental criteria.
[14]	Proposed an AHP-based methodology for determining EOL options for general paper products, including printing paper, coated paper, newsprint paper, cardboard, and paperboard. They concluded that the majority of paper products are highly suitable for recycling. However, coated paper was recommended for incineration due to its limited recyclable quality.
[15]	Introduced an Extended Pythagorean Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to select sustainable recycling partners. They thoroughly investigated environmental, social, and economic parameters based on current sustainable practices to develop an evaluation system for recycling partners.

2. Materials and Method

2.1.1 Analysis Hierarchy Process (AHP)

AHP is a structured technique for organizing and analyzing complex decisions by breaking them down into a hierarchy of criteria and alternatives, and then assessing the relative importance of each criterion and the performance of each alternative against those criteria [22], [23], [24]. This method systematically evaluates and selects the best EOL option for thermoplastic used in 3D printing, considering various criteria and their relative importance [24]. The procedure of MCDA using AHP is presented in Fig 1.

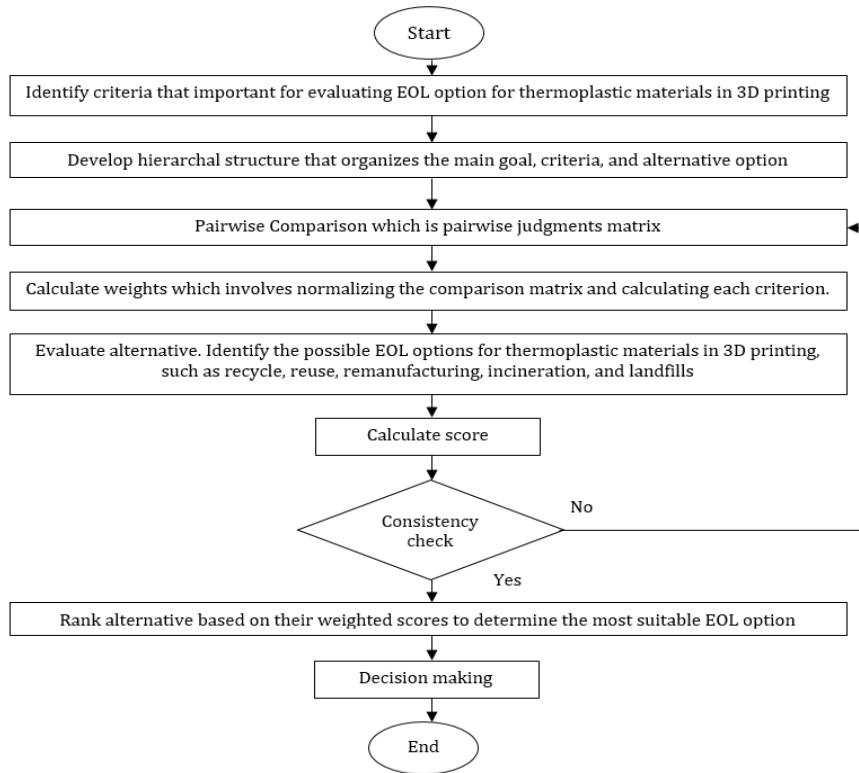


Fig. 1 Flowchart of procedure

The assessment scale for pairwise comparisons as implemented in the AHP method is shown in Table 2. In the decision-making of AHP method, the intensity of importance scales indicates the degree to which one criterion or objective is preferred over another. A scale of 1 to 9 is used, where 1 indicates equal importance, 3 signifies moderate preference, 5 indicates strong preference, 7 represents very strong preference, and 9 indicates extreme preference. Intermediate values (2, 4, 6, 8) are used to express varying degrees of compromise when preferences are not absolute. Reciprocals such as 1/2, and 1/3 are used for inverse comparisons where one criterion is considered less important relative to another. These scales help quantify subjective judgments and preferences in decision-making processes by assigning numerical values that reflect the relative importance or preference of each criterion being evaluated.

Table 2 Evaluation scales for pairwise comparison [25]

Intensity of importance	Degree of preference	Explanation
1	Equally	The importance of each objective is equal
3	Moderately	Attribute is slightly favoured over another
5	Strongly	Experience and judgement strongly or essentially favour one activity over another
7	Very strongly	Attribute is very strongly favoured over another
9	Extremely	The evidence of favouring one activity over another is of the highest degree possible of an affirmation
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals	Opposites	Used for inverse comparison

Meanwhile Table 3 provides the definitions of input, processing, and output for an AHP-based program. The table provides a clear and structured framework for understanding the development of graphical user interface (GUI). A user-friendly GUI was created to enhance usability based on the structured methodology [25]. The input section includes the weightage of main criteria (resource, environmental impact, economic value, and legislative priority) and the judgement between five EOL options (recycle, reuse, remanufacturing, incineration, and landfills) within each criterion. The processing section details the steps to establish structural hierarchies, construct the pairwise comparison matrix, derive the eigenvector and maximum eigenvalue, calculate the

consistency ratio (CR), and develop overall weight or priorities. The output section provides the best EOL option for each component, evaluates the consistency and acceptability of the user's judgement, and determines the importance ratings of EOL options based on their percentage usage across all components.

Table 3 Definitions of input, processing, and output for AHP-based program [14]

Input	Processing	Output
a. Weightage of main criteria (Resource, Environmental impact, Economic value, and Legislative priority)	a. Establish structural hierarchies.	a. The best EOL option for each component.
b. The judgement between 5 EOL options within each criterion (Recycle, Reuse, Remanufacturing, Incineration, Landfills)	b. Establish the pairwise comparison matrix.	b. Consistency and acceptability of the user's judgement.
	c. Derive eigenvector and maximum eigenvalue.	c. Importance ratings of EOL options based on the percentage usage among all components.
	d. Derive the consistency ratio (CR).	
	e. Develop overall weight or priorities.	

2.2 Case Study Description

This case study delves into the application of MCDA to evaluate the EOL option for thermoplastics of 3D printing. With the growing adoption of additive manufacturing, managing the disposal and recycling of thermoplastic waste has become a critical concern. Through MCDA, this study aims to identify and prioritize various criteria such as resources, environmental impact, economic value and legislative priority compliance to assess the most suitable EOL option for thermoplastics used in 3D printing. By employing MCDA methodologies, the study provides a structured approach to decision-making, facilitating informed choices that aligning with sustainability goals while considering practical constraints within the 3D printing industry. The hierarchy prioritizes reducing waste at its source, followed by recycling and reuse, with landfill disposal viewed as a final option. In this study, EOL options include recycling, remanufacturing, reuse, incineration, and landfill.

3. Results and Data Analysis

This section presents the key findings obtained from the case study, alongside a detailed analysis of the data collected. The results are interpreted with a focus on identifying the EOL options of 3D Printing Thermoplastic.

3.1.1 Application of AHP Method

AHP methods were employed to ensure reliability of the data and analyzed the complex decisions. The analysis also highlights the best alternative for handling materials such as PLA, ABS, and PEEK by using AHP-based program. **(i)** Identification of criteria: The identification of criteria is based on the goal of the study. For this study, the goal is to identify the best EOL options for thermoplastic materials in 3D printing. Therefore, the selected criteria for the first level of hierarchy structure are resource, environmental impact, economic value, and legislative priority. The sub criteria were also added in the criteria listed and some alternatives options was chosen based on the criteria listed which are recycle, reuse, remanufacture, incinerate, and landfills. **(ii)** Hierarchy Structure: Fig. 2 shows the developed hierarchical structure of AHP method for this study consist of 3 level which are the upper level, Level 0 for the goal, Level 1, criteria and the last one is Level 2 which is the alternatives options. **(iii)** Pairwise Comparison and Weightage Scoring: There are 4 pairwise comparison matrices involved for level 1 and 5 matrices for level 2. Table 3 shows the sample pairwise comparison based on weightage scoring of matrix level 1 respect to the goal.

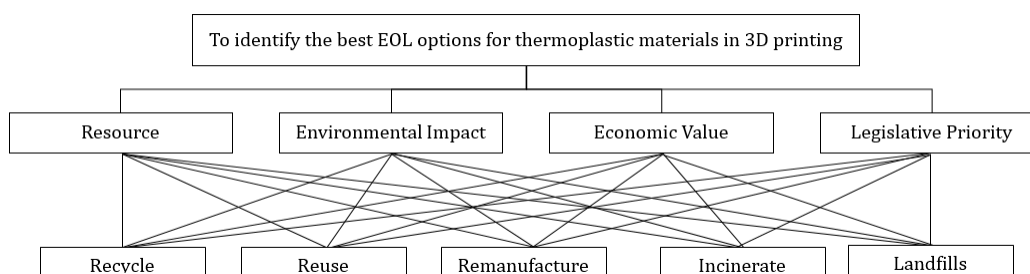


Fig. 2 Hierarchy structure

Table 3 Scoring for factor of level 1

Choices	Resources	Environmental Impact	Economic value	Legislative priority	Priority
Resources	1	4	2	5	47.82%
Environmental impact	0.25	1	0.33	4	15.70%
Economic value	0.50	3	1	4	29.62%
Legislative priority	0.20	0.25	0.25	1	6.85%
Sum	1.95	8.25	3.58	14	100%

(iv) Scoring Judgement: The scoring judgement is evaluated for all three selected 3D printing materials: PLA, ABS, and PEEK. The methods utilized to make the decisions, and the final outputs produced. Every product has five possibilities for EOL which are the alternative options. Table 4 until Table 7 presents data for λ_{max} , consistency Index (CI), and CR values for each material. This data can be derived by insert the evaluation scale values for pairwise comparisons into the AHP-based program. The CR values for each material were found to be below 10%, indicating acceptable consistency. The CR value was calculated using ratio index (RI) value based on each scoring for 5 comparisons. In this study all data were automatically generated within AHP-based program.

Table 4 CR value for resource factor

Types of 3D printing material	λ_{max}	CI	CR
PLA	5.147	0.037	3.3%
ABS	5.383	0.096	8.5%
PEEK	5.390	0.097	8.7%

Table 5 CR value for environmental impact factor

Types of 3D printing material	λ_{max}	CI	CR
PLA	5.4	0.1	8.9%
ABS	5.256	0.064	5.7%
PEEK	5.425	0.106	9.5%

Table 6 CR value for economic value factor

Types of 3D printing material	λ_{max}	CI	CR
PLA	5.312	0.078	7.0%
ABS	5.356	0.089	7.9%
PEEK	5.351	0.088	7.8%

Table 7 CR value for legislative priority factor

Types of 3D printing material	λ_{max}	CI	CR
PLA	5.165	0.041	3.7%
ABS	5.430	0.108	9.6%
PEEK	5.423	0.106	9.4%

3.1.2 AHP-based Program

The procedure for determining the most suitable thermoplastics for 3D printing, by employing AHP analysis, was carried out exclusively in Microsoft Excel. For AHP analysis, users are required to input values for each criterion and the EOL option. By clicking the calculate button, the program automatically generates data pertaining to the EOL option. Users are required to delete any previously entered information prior to saving the results and entering additional data. In this analysis, the main criteria involved resources, environmental impact, economic value and legislative priority, and as shown in Fig. 3. Fig. 4 until Fig. 7 illustrate examples of GUI for each criterion. Furthermore, an analysis was conducted on the three chosen 3D printing materials, namely PLA, ABS, and PEEK.

The decision-making processes were documented, and the resulting composite weights were visually represented in Fig 8. At EOL, each product will be subject to one of four options: recycling, remanufacturing, reuse, incineration, or disposal in a landfill. Therefore, the highest percentage signifies its superiority in comparison to the alternative options that are present.

PRODUCT NAME:	ABS					
Main Criteria	Resource	Environmental Impact	Economic Value	Legislative Priority	Priority	
Resource	1.00					
Environmental Impact		1.00				
Economic Value			1.00			
Legislative Priority				1.00		
Sum						100.00%
λ max						
CI						
CR						

Fig. 3 Main interface

FACTOR A	RESOURCE					
Choice	Recycle	Remanufacture	Reuse	Incinerate	Landfill	Priority(%)
Recycle	1.00					
Remanufacture		1.00				
Reuse			1.00			
Incinerate				1.00		
Landfill					1.00	
Sum						100.00%
λ max						
CI						
CR						

Fig. 4 Resource interface

FACTOR B	ENVIRONMENTAL IMPACT					
Choice	Recycle	Remanufacture	Reuse	Incinerate	Landfill	Priority(%)
Recycle	1.00					
Remanufacture		1.00				
Reuse			1.00			
Incinerate				1.00		
Landfill					1.00	
Sum						100.00%
λ max						
CI						
CR						

Fig. 5 Environmental impact interface

FACTOR C		ECONOMIC VALUE				
Choice	Recycle	Remanufacture	Reuse	Incinerate	Landfill	Priority(%)
Recycle	1.00					
Remanufacture		1.00				
Reuse			1.00			
Incinerate				1.00		
Landfill					1.00	
Sum						100.00%
λ max						
CI						
CR						

Fig. 6 Economic value interface

FACTOR D		LEGISLATIVE PRIORITY				
Choice	Recycle	Remanufacture	Reuse	Incinerate	Landfill	Priority(%)
Recycle	1.00					
Remanufacture		1.00				
Reuse			1.00			
Incinerate				1.00		
Landfill					1.00	
Sum						100.00%
λ max						
CI						
CR						

Fig. 7 Legislative priority interface

	Factor A	Factor B	Factor C	Factor D	Composite weight
Adjusted weight					
Recycle					
Remanufacture					
Reuse					
Incinerate					
Landfill					
CALCULATE					

Fig. 8 Compositated weight interface

3.2 Result Analysis

Following the evaluation of each material, a list of the materials' composite weights was produced. The result demonstrates that 3D printing materials are preferable to be recycled over satisfying all other requirements. The composite weight result for each EOL choice of 3D printing material is displayed in Table 8. This composite weight is automatically generated from the AHP-based program for all factors which are recycle, remanufacture, reuse, incinerate, and landfill.

Table 8 Composite weight for 3D printing materials

No	Material	Recycle	Remanufacture	Reuse	Incinerate	Landfill
1	PLA	45%	16%	24%	10%	5%
2	ABS	48%	22%	19%	7%	4%
3	PEEK	50%	18%	21%	7%	4%

AHP method was utilized to collect data and determine the best options for handling different materials. In the case of PLA, recycling emerged as the most favorable option, with 45% of composite weight allocated to it, while only 5% was designated for landfill. Recycling PLA involves melting it down for reuse as filament or other

products. Despite being biodegradable, PLA products do not decompose easily in compost or landfills, with only 1% expected to decrease after 100 years, thus landfill disposal has minimal environmental impact. Similarly, ABS showed recycling as the preferred option, with 48% allocated to it and only 4% to landfill. ABS recycling helps mitigate plastic waste in landfills and incinerators, reducing environmental harm. For PEEK, recycling was also identified as the best option. PEEK is a high-performance engineering material with valuable properties, making recycling at its EOL stage important for preserving its qualities and conserving resources for future use.

4. Discussion

Based on the results of the AHP-based program, it is clear that recycling is the best alternative for handling materials such as PLA, ABS, and PEEK in terms of sustainability. This highlights the significance of prioritizing recycling as a key strategy in sustainable materials management practices. It is important to explore the ways to improve recycling procedures for each of the material types highlighted in the study. For example, in the case of PLA, which is recognized for its biodegradability but has limited breakdown in landfills, more research into improving recycling processes such as melting down for reuse might assure optimal resource recovery. Similarly, the development of enhanced recycling systems that can efficiently manage ABS and PEEK, potentially on a large scale, could be considered a primary objective. By investing in research and development (R&D) in this area, industries can move towards more sustainable practices while maintaining the quality and performance of these materials.

Furthermore, the implications for sustainability management in thermoplastic of 3D printing are evolving, and they can have a substantial influence on different areas of technology adoption and use. By incorporating sustainable practices such as EOL considerations, recycling, and resource efficiency, 3D printing has the potential to substantially reduce its adverse environmental effects. This can be achieved by minimizing waste generation associated with the production and disposal of printed materials. Besides, sustainable practices in 3D printing, such as material recycling and waste reduction, can lead to cost savings. By minimizing material waste and optimizing resource utilization, companies can lower production costs and improve overall profitability.

In addition, the challenges associated with EOL considerations in thermoplastic 3D printing are numerous and have significant difficulties in achieving sustainable waste management practices. These challenges include the complexity of thermoplastic materials, contamination issues, degradation concerns, limited recycling infrastructure, regulatory hurdles, economic viability constraints, and consumer awareness gaps. To address these issues, industry players must work together to establish standardized recycling procedures, invest in effective recycling technology, promote eco-design principles, and increase knowledge about the value of sustainable practices. By overcoming these challenges, the 3D printing industry can move towards a more circular and sustainable ecosystem, minimizing waste generation, conserving resources, and reducing environmental impacts.

5. Conclusion

This study presents the creation and use of a standardized MCDA framework designed to determine the best EOL approach for disposing of thermoplastic materials produced by 3D printing. This technology makes a substantial contribution to the environmental stewardship of the additive manufacturing (AM) ecosystem by incorporating sustainability and resource efficiency. This approach is based on the AHP and involves comparing EOL choices with a selected set of important criteria and stakeholder preferences. This ensures a comprehensive review of prospective strategies. Not only has the implementation of this study accomplished its initial objectives, but it has also surpassed them, signifying a noteworthy triumph within the confines of its goals. This inquiry significantly advances sustainable manufacturing processes by introducing a new methodology, providing practical disposal strategies, and creating a user-friendly Microsoft Excel interface. The evaluative framework relies on a comprehensive analysis of existing literature on different EOL strategies, such as recycling, reuse, remanufacturing, incineration, and landfilling. This framework takes into account factors like resource utilization, environmental impacts, economic feasibility, and legislative compliance. Although the results of this study may not apply to every field, they unquestionably provide an improved, customized solution that meets the individual requirements and preferences of the user group. Moreover, the implementation of an AHP-based software, created using Visual Basic for Applications (VBA), improves the user interface by streamlining the data input and result generation for EOL choices. Initially, the program focuses on PLA, ABS, and PEEK materials, but it can also accommodate other material considerations. Overall, this study successfully accomplishes its stated goals and also sets the stage for future progress in the sustainable handling of 3D printing waste. It provides a strong basis for decision-makers to navigate the challenges of selecting EOL strategies in the rapidly changing field of additive manufacturing.

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Conflict of Interest

The authors would like to declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Salwa Mahmood, Mohammad Azwan Azit Kesumar; **data collection:** Tuan Nurin Nabila Tuan Mohammad Suzani; **analysis and interpretation of results:** Tuan Nurin Nabila Tuan Mohammad Suzani, Nurul Ainina Nadhirah Tajurahim, Salwa Mahmood; **draft manuscript preparation:** Tuan Nurin Nabila Tuan Mohammad Suzani, Nurul Ainina Nadhirah Tajurahim, Salwa Mahmood. All authors reviewed the results and approved the final version of the manuscript.*

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