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Evaluating Additive Manufacturing in User-Centered Design: Analytical Hierarchy Process Approach

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***Abstract* - Additive Manufacturing (AM) otherwise called 3D printing, its industrial application is increasingly shifting from mere product design to flexible process reimagination, user-centric development and decision-driven. This study highlights the importance of considering the preference AM process to facilitate needs in Product Service System (PSS). The current Design for Additive Manufacturing (DfAM) approaches are not well-suited for individuals new to the use of AM in product design because of connection with the direct application of familiar conventional manufacturing methods. To tackle this, this study proposes an approach that considers the user's preference based on the Analytical Hierarchy Process (AHP) to select the feasible and suitable AM technology. The proposed AHP decision matrix is validated in a study for a brake disc application, demonstrating its alignment with the weights obtained from real-world scenarios. This approach is effective being a theory of inventive problem-solving approach used in systematic analysis that generates innovative solutions for design problems. The study contribution provides valuable decision support for designers to help prioritize factors or criteria related to additive manufacturing design objectives.**

***Index Terms* - Additive Manufacturing, Product-Service System, User-Centred Design, Analytical Hierarchy Process.**

INTRODUCTION

The advent of Additive Manufacturing (AM) has transformed the approach to designing, producing, and disseminating products and ushering in a revolutionary shift in the manufacturing landscape. It is a digital manufacturing process which involves the creation of a product from 3D model. In comparison to the conventional manufacturing approach, in the AM concept, material builds upon the other, thus, significantly reducing material and energy use [1]-[2].

AM provides not only design flexibility advantages but also opens up opportunities for enhancing products through the incorporation of novel manufacturing technologies and processes [3]-[5]. Moreover, AM holds the capability to reform the way companies deliver their products and services by enabling customised and personalised products and services that align with specific needs and preferences [6]. To maximize this beneficiating manufacturing technology, practical design frameworks or methodologies must be developed. To promote product performance function and accelerate the adoption of innovation bringing about the concept of user-centered designs requires a suitable AM technique [7]. The existing Design for Additive Manufacturing (DfAM) methods face limitations of failure to incorporate the assessment of the suitable AM processes during the initial design phase and predominantly depend on the straightforward utilization of established methods used in traditional manufacturing.

Product Service System (PSS) is a peculiar model that integrates a serviced product function in a unified system in delivering value to users [8]. In turn, a comprehensive and customized solution that includes the related services of a product is met. AM is gaining meaningful spreads in production in a variety of industries, such as aerospace, medical device and automotive industries [4]. According to a survey report from 2022, 3D printing has been employed by 66% of users for educational, research and development (R&D) purposes; 69% for producing mechanical components; 40% for post-purchase services, spare parts, and replacements; 23% for manufacturing personalized products; 37% for creating final useable products; 49% for crafting tools, and 1% for various undefined other applications [9].

On the other hand, 41% of companies acknowledged that AM enhances efforts in meeting sustainability goals, 89% of survey participants regard AM as a pivotal element contributing to a competitive advantage in their corporate growth strategy, and 84% display high optimism regarding the future potential of AM [2]. Consequently, the transformative potential of AM technology and its capacity to confer a competitive edge upon organizations has been apparent in recently.

In exploring the 3D printing technology, the hurdles associated with its adoption have also garnered substantial attention in academic research [2]. Numerous difficulties highlighted in prior studies include high costs AM [10], the persistently slow production speeds [9], the inadequate array of materials [11]. In addition, the challenge of altering designers' perspectives [12], paucities in organizational knowledge and awareness [2], insufficient management and control support [12], and a dearth of adequate infrastructure [5]. AM can produce customized and personalized products with a high level of complexity, reducing lead times and increasing the flexibility of the production process. However, there is still a lack of understanding of how to use AM to aid PSS involving a user-centered approach [6]. Therefore, this study aims to explore the use of AM design using a user-centered approach.

Over the past few years, the vision of an industrial additive technology replacing some of the manufacturing processes is now almost a reality with flexible product design and modification. The adoption of AM is a more benefiting in cases where there is desire for end-user customization and production of small volume intricate high-end product requiring quality assurance is needed beyond traditional means [6]. With technical standards, the AM industry has gradually progressed beyond mere prototyping towards final production. Nonetheless, studies emanating from different Research and Development (R&D) fields indicate concern on the selection of suitable AM for use and AM technique decision-making [13]. Manufacturing firms require indepth information for producers in understanding the key element in selecting accurate AM for a seamless production system. As such, knowledge assessment is required for optimal decision, as there are only few studies touching on development of the right cross-decision solution [13]. Therefore, based on a holistic framework, this study sort after to identification and assessment of the appropriate AM that can be employed in the design and production process applicable to brake disc design using approaches of Multi-Criteria Decision Making (MCDM) such as Analytical Hierarchy Process (AHP), to help in determining criteria for conflicting decision making. The novel solution this study looks into is the model of AM selection through user knowledge.

LITERATURE REVIEW

The literature review highlights the importance of considering the user's design process. Emphases include the need for an appropriate framework that considers the user's needs, design requirements, and technology capabilities. The use of AM design in Product Service System (PSS) can offer many benefits, such as the ability to create customized products and services, the ability to rapidly prototype and iterate designs, and the ability to create intricate products. PSS was a response to the need to make manufacturing and usability of product sustainable. For instance, decreasing waste through reuse, remanufacturing, or repair is consistent with the modern gear of a circular economy in sustainable development [14].

Despite the potential benefits of using AM in PSS design, lack of understanding of how best to integrate AM into PSS design is key. There is a need for more user-centered approaches to enable AM design in PSS. Figure 1 presents the concept of PSS being the generic life cycle of product and service as a discourse for AM sustainability [15]. PSS is distributed into four segments, namely; Design (product and process), Production (component manufacturing, material processing, raw material extraction), Customers (services and use), and Closing the loop (other by-products).

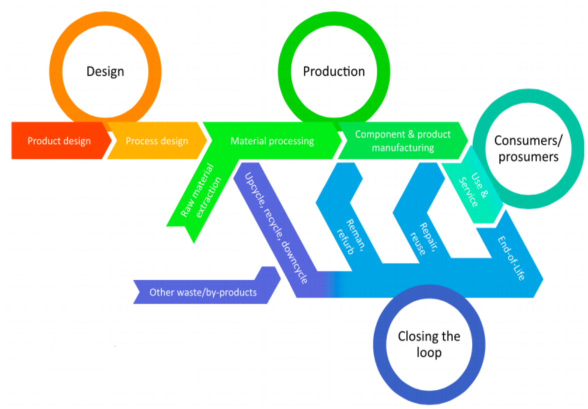

FIGURE 1 PRODUCT SERVICE SYSTEM SEGMENTATION FOR SUSTAINABILITY IN AM

Going by the presented segmentation of the four phases of PSS for AM sustainability, product and process design in an innovative way to improve contribution to manufacturing efficiency.

I. Evolution of Product Development using AM

The conventional approach to product development typically centres around the stages of conceptualization, design, production, emphasizing a combination of intuition and a technology-driven strategy.

Traditionally, companies have given priority to the product itself, often overlooking the critical aspect of understanding user needs within a target market and incorporating user input throughout the development process [16]. This reliance on intuition and a technology-centric push strategy has led to challenges in getting the design right initially, resulting in expensive product failures and prolonged time-to-market.

In competitive markets, only a small percentage, approximately 1 or 2%, of innovative ideas ultimately translate into successful and sustainable products. This underscores the importance of re-evaluating the conventional approach to product development, placing greater emphasis on understanding and incorporating user insights as primary factors rather than treating them as secondary variables.

AM has significantly penetrated production in three key industries: aerospace, medical, and automotive. In the aerospace sector, the unique advantages of AM are particularly well-suited for addressing challenges associated with high costs and low production volumes. This is evident in the production of satellite components, typically manufactured in limited quantities, and even high-volume aircraft, which are generally produced in 100's and even lower than 1000's. AM's strengths become apparent in aerospace due to the substantial cost savings derived from reduced material waste, especially considering the use of expensive materials like titanium. The nature of the production process allows for a more efficient utilization of these materials, contributing to significant economic advantages. Additionally, the stringent quality requirements in aerospace manufacturing necessitating thorough inspections, align with the capabilities of AM for brake disc application. Notably, traditional machining processes were already subject to rigorous quality control, making the transition to AM seamless in terms of meeting these standards. A prime example of metal AM in mass production is exemplified by the General Electric (GE) LEAP fuel nozzle. This serves as a noteworthy instance where AM technology has been successfully employed on a larger scale of 20 parts merged to form 1, reduction in weight of 25%, and improved reliability through part count reduction. GE printing of the fuel nozzle production started in 2015 and towards end of 2018, 30,000 units in production rate approximating 7,500 in a year. This showcases its potential for high-volume production while maintaining the precision and quality demanding usability.

The manufacturing domain system is determined by the interplay of process and operational parameters influenced by input. Traditional analytical methods prove impractical for enhancing performance, it is recommended to employ simulation tools in conjunction in experimental design and statistical analysis for better results. [17]. Table I presents the concept of product development design adapted from [17].

TABLE I
DESIGN CYCLE FOR PRODUCT DEVELOPMENT

	Process of Product Development			
	Investigation	Production	Simulation	Evaluation
Work strategy	Task plans and product study analysis	Generating task structures and forming solution ideologies	Create basic design blueprints and formation. Augment and assess against techno-economic criteria	Optimize and factorize design forms. Examine errors and consider effectiveness of cost. Prepare for part and production

II. Additive Manufacturability Techniques

The inception of additive manufacturing (AM), widely recognized as 3D printing can be traced back to the era of 1940s [18]. Its popularity soared following the expiration of patents for the printing process of Fused Deposition Modelling (FDM) in 2009. Over the years, AM has progressively entered the automotive market, accompanied by a continual decrease in 3D printer prices. Affordable FDM printers have become prominent within the RepRap users, FabLab, maker spaces, and in other manufacturing enterprises. Terms often used interchangeably within the broader concept of AM are rapid manufacturing (RM), rapid prototyping (RP), solid freeform fabrication (SFF) and direct digital manufacturing (DDM). At present, industrial production utilizes a variety of AM technologies, encompassing the likes of Fused Filament Fabrication (FFF), Stereolithographic (SLA), Digital Light Synthesis (DLS), Jet Fusion, Digital Light Processing (DLP), Polyjet, Selective laser sintering (SLS), Direct Metal Laser Sintering (DMLS) or Selective Laser Melting (SLM), Binder Jetting, and more evolving ones [3], [4], [16], [19].

AM offers notable advantages, including the ability to produce highly customized items in terms of size and shape, eliminating the need for additional post-machining processes and reducing costs. AM facilitates the use of various materials, allowing for the fabrication of intricate parts. The synergy between topology optimization and AM enables the creation of lighter parts, optimizing material usage. Additionally, AM expedites product development, aligning with User-Centered Design (UCD), which prioritizes user needs throughout the development process. UCD ensures end users are considered at every stage, enhancing the likelihood of meeting their requirements and simplifying the overall AM-enabled Product-Service System (PSS) design process.

III. Conditions for Evaluating AM's User Behaviour

The need to consider both product and manufacturing process is acknowledged in the literature, with the widely recognized Design for Additive Manufacturing (DfAM) guideline described by [20]. From the perspective of DfAM, the existing approaches documented in literature identify bottleneck challenges in AM adoption for commercial use and the proposed specific areas for attention are:

- Examination of AM principles, despite being commonly treated as a unified technology. AM processes diverge significantly in principles and mechanisms, resulting in considerable variations in the characteristics of printed parts. As such, users often lack the essential understanding of the decisions in different AM processes.
- Another noted issue in AM process is selection system. This is relation to performance evaluation, which rely on the quality of information provided and suggested [21]. The performance of AM processes are essential for users to make well-informed decisions on process selection and instill confidence
- Performance description in AM is a concern influenced by mixed factors. Materials, process parameters, post-processing, machine condition, machine operation and so on requires varying to achieve purpose.

The study perspective is that a non-sequential decision-making model would be more beneficial, allowing users to adapt or create designs that align with an AM process [22]. The method used to facilitate this kind of approach is the technique known as a posteriori articulation of preferences [23].

This method allows decision makers and end users to choose from a range of solutions without clearly specifying preferences or provide specific values. In addition, this study is based on a proposed framework of evaluation model for decision-making in AM. This would assist in the context of identifying the right AM candidate and emphasizing user design. The proposed model in consideration is the use of Analytical Hierarchy Process (AHP) to rank criteria according to case application needs. The proposed decision matrix is validated with a brake disc, demonstrating its alignment with the weights obtained from real-world scenarios.

METHODOLOGY

Most of the existing design processes adapt for any AM of choice once the concept is finalised, rather than designing for AM. Therefore, this study focuses on the development of an optimization driven methodology that carefully inculcates AM design principles in the stages of conceptualization. This section compares the AM techniques that can be employed for the development of the brake disk component and selects the most feasible one using the Analytical Hierarchy process. Thereafter the behaviour of the component using the selected process was investigated using the Finite Element Method (FEM).

The proposed AM approach include the Electron Beam Melting (EBM), Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Stereolithography (SLA), and Fused Deposition Modelling (FDM). Table II presents the comparative analysis of the feasibility of the proposed AM techniques.

TABLE II
FEASIBILITY COMPARATIVE ANALYSIS OF THE PROPOSED AM TECHNIQUE

AM techniques	Pros	Cons	Applications	References
Electron Beam Melting (EBM)	- It is highly suitable for metal parts to create customised products. It combines reliability, speed, and versatility. It is relatively fast, less labour-intensive and cost effective for low volume requirements.	- Need for processing which may consume more materials. There is tendency for increase in the production time and cost due to post-processing. It is exclusively used in metal with limited build volume	Aerospace industry and orthopaedic medical implants, automotive	[24]-[28]
Selective Laser Melting (SLM)/Selective Laser Sintering (SLS)	- Provision of recycling option for the materials. It can be used for producing materials where strength and quality are requirements. Suitable for manufacturing of parts with complex geometry	- Energy-intensive. Need for processing which may consume more materials. There is tendency for increase in the production time and cost due to post-processing. It also requires consumables such as inert gas	Aerospace and orthopaedic, dental and biomedical industries	[24]-[28]
Stereolithography (SLA)	- SLA is suitable for clear and transparent product. Uses biocompatible materials, with low residue, reduction energy consumption. Suitable for the manufacturing of parts with complex geometry. Time and cost effective for production of multi-part assemblies.	- Pre-processing in is energy-intensive, contribute to greenhouse gas emissions. Low material consumption and single-stage production without post-processing. However, limited to photosensitive resin, and parts heat-susceptible, making it unsuitable for industrial requirements.	Biomedical applications	[28]
Fused Deposition Modelling (FDM)	- The raw material consumption is low and provides the option of material recycling. The process residues generated are low. Cost and time effective.	- Processing stage is energy intensive, contributing to environmental pollution in form of eutrophication. Support structure sometimes need post-processing. Low in resolution, not ideal for intricate details.	Aerospace, medical, automotive, and architectural industries	[29]
Wire Arc Additive Manufacturing (WAAM)	- Suitable for producing highly complex parts with increased flexibility. Considerable material and energy saving	- Poor resolution and surface finish. There may be a need for post-processing	Aerospace, marine, material tooling, oil and gas industries	[28]

Amongst other requirements, a brake disc should have high strength and stiffness at high temperatures, high thermal conductivity, excellent abrasion, corrosion, and creep resistance.

Therefore, the following are the criteria used for the selection of the most feasible AM technique [30]-[31]

- Service and functional requirements
- Energy consumption and environmental friendliness
- Time and cost-effectiveness of the process
- Quality of the final product and the need for post-processing

According to Muvunzi *et al.* [30]-[31], it becomes necessary for cost and time reasons to avoid post-processing and achieve the desired product quality during the initial production process. Sometimes, the process of post-processing may alter the desired service and functional requirements of the product thus reducing it to a scrap. Furthermore, achieving the intended service and functional requirements is also an important factor to avoid reverse engineering. This will also contribute positively to customer satisfaction level, appraisal and feedback. There is a need for manufacturing industries to consider the energy consumption of their manufacturing processes to reduce carbon footprints to make the products manufactured environmentally friendly throughout its lifecycle. In addition, time effectiveness is important to reduce the manufacturing lead time while cost effectiveness is central to achieving the organisation's bottom-line goal of profitability. The Analytical Hierarchy Process (AHP) was employed as a scientific computational decision support model for determining the most feasible AM technique to be employed for the production of the considered case application for a brake disc. Coyle [32] indicated that the AHP can solve multiple criteria problems to make an informed decision.

AHP is a decision support framework that can be used for structuring a multi-decision problem and evaluation of the criteria and the alternatives vis-à-vis the overall goal [33]-[34]. In doing so, the weights of each of the criteria can be compared followed by the ranking of the alternatives [35]. The pairwise comparisons will allow decision to make comparison of the alternatives and select the most feasible one [36].

The first step is to identify the overall goal, criteria or alternatives. In the context of this study, the overall goal is to investigate the feasibility of using the additive manufacturing technique to develop a brake disc as opposed to the conventional manufacturing technique. The criteria include the investigation of the energy consumption and environmental friendliness of the AM process employed, the time and cost effectiveness of the process, quality of the final product as well as the service requirements. The alternatives are the different AM techniques by which the brake disc can be developed. These include the EBM, SLM/SLS, SLA, FDM and WAAM.

The problem is decomposed into a structure based on the criteria and the competing alternatives. After that, weights are allocated to the criteria and a pairwise comparison of the weights of the criteria was carried out. To determine how consistent, the decision of weight allocation is, a consistency check is usually carried out. When the consistency exceeds 10%, the reallocation of the weights was carried out [37]. Table III presents the pairwise comparison scale for AHP for weight allocation.

TABLE III
PAIRWISE COMPARISON SCALE FOR AHP

Weight	Decision
9	Extremely preferred
8	Very strongly to extremely
7	Very strongly preferred
6	Strongly to very strongly
5	Strongly preferred
4	Moderately to strongly
3	Moderately preferred
2	Equally to moderately
1	Equally preferred

According to Akinbowale et al. [38], the pairwise comparison is usually, followed by the ranking of the criteria in relation to the overall goal [38]. The process of pairwise comparison leads to the formation of a square matrix A, thus, Equation (1) presents the right eigenvector (xx) and scalar quantity (λ)λ).

$$Ax = \lambda x \quad (1)$$

where:

A is the square matrix, xx is the right eigenvector; and $\lambda\lambda$ is the scalar quantity.

Equations (2) and (3) present the Consistency Index (CI) and the Consistency Ratio (CR) respectively for the determination of the consistency level of the weights allocated to the criteria. The level of consistency is judged to be low when the CR exceeds 10% and a re-assignment of the weight will be required [37].

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

where: $\lambda_{max}\lambda_{max}$ is the maximum eigenvalue, n is the number of criteria and $RIRI$ is the Random Consistency Index as indicated by [37]. Figure 2 presents the structuring of the multi-criteria problem while Table IV presents the paired comparison of the criteria and the resulting priority vector.

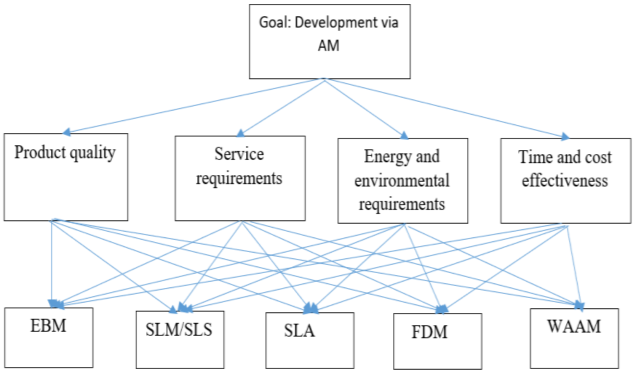

FIGURE 2 THE STRUCTURING OF THE MULTI-CRITERIA PROBLEM.

TABLE IV
THE PAIRED COMPARISON OF THE CRITERIA AND THE RESULTING PRIORITY VECTOR (6 COMPARISONS)

Criteria	PQ	SR	EQR	TCE	Priority vector (%)	Rank
Product quality (PQ)	1.00	1.00	1.00	5.00	31.00	2
Service requirements (SR)	1.0	1.00	2.00	7.00	39.80	1
Energy and environmental requirements (EQR)	1.00	1/2	1.00	3.00	22.90	3
Time and cost effectiveness (TCE)	1/5	1/7	1/3	1.00	6.40	4
Sum	3.20	2.64	4.33	16.00	100.1	

From Table IV, the principal Eigen value and the consistency ratio were calculated as 4.055 and 2.0% respectively. This implies that the weight allocation to the competing criteria and the pairwise comparison process were consistently carried out since the CR<10%.

Tables V-VIII present the pairwise comparison of the competing factors (types of AM techniques) and their relative weights for the identified criteria. The weights were allocated basis on the pros and cons of the AM techniques highlighted in Table II and based on their relative importance according to Table III.

TABLE V
THE FACTORS (TYPES OF AM TECHNIQUE) AND THEIR PAIRWISE WEIGHTS IN RELATION TO THE FIRST CRITERION (PRODUCT QUALITY) (10 COMPARISONS)

Factor	EBM	SLM /SLS	SLA	FDM	WAAM	Priority vector (%)	Rank
EBM	1.00	3.00	5.00	7.00	3.00	48.10	1
SLM/ SLS	1/3	1.00	3.00	5.00	1.00	22.30	2
SLA	1/5	1/3	1.00	1.00	1.00	8.90	4
FDM	1/7	1/5	1.00	1.00	1.00	7.80	5
WAAM	1/3	1.00	1.00	1.00	1.00	12.90	3
Sum	2.00	5.53	11	15.00	7.00	100	

From Table V, the principal Eigen value and the consistency ratio were calculated as 5.251 and 5.6% respectively. This implies that the weight allocation to the competing criteria and the pairwise comparison process were consistently carried out since the CR<10%.

TABLE VI
THE FACTORS (TYPES OF AM TECHNIQUE) AND THEIR PAIRWISE WEIGHTS IN RELATION TO THE SECOND CRITERION (SERVICE REQUIREMENTS) (10 COMPARISONS)

Factor	EBM	SLM/ SLS	SLA	FDM	WAAM	Priority vector (%)	Rank
EBM	1.00	1.00	3.00	5.00	7.00	38.70	1
SLM/SLA	1.00	1.00	1.00	3.00	7.00	27.40	2
SLA	1/3	1.00	1.00	3.00	3.00	19.40	3
FDM	1/5	1/3	1/3	1.00	5.00	10.30	4
WAAM	1/7	1/7	1/3	1/5	1.00	12.904.20	5
Sum	2.67	3.47	5.66	12.50	23.00	100	

From Table VI, the principal Eigen value and the consistency ratio were calculated as 5.305 and 6.80% respectively. This implies that the weight allocation to the competing criteria and the pairwise comparison process were consistently carried out since the CR<10%.

TABLE VII
THE FACTORS (TYPES OF AM TECHNIQUE) AND THEIR PAIRWISE WEIGHTS IN RELATION TO THE THIRD CRITERION (ENERGY AND ENVIRONMENTAL REQUIREMENTS) (10 COMPARISONS)

Factor	EBM	WAAM	SLA	FDM	SLM/ SLS	Priority vector (%)	Rank
EBM	1.00	3.00	3.00	3.00	3.00	41.10	1
WAAM	1/3	1.00	1.00	1.00	3.00	16.80	3
SLA	1/3	1.00	1.00	2.00	5.00	22.10	2
FDM	1/3	1.00	1/2	1.00	1.00	11.60	4
SLM/ SLS	1/3	1/3	1/5	1.00	1.00	8.20	5
Sum	2.33	6.33	5.70	8.00	13.00	99.8	

From Table VII, the principal Eigen value and the consistency ration were calculated as 5.291 and 6.5% respectively. This implies that the weight allocation to the competing criteria and the pairwise comparison process were consistently carried out since the CR<10%.

TABLE VIII
THE FACTORS (TYPES OF AM TECHNIQUE) AND THEIR PAIRWISE WEIGHTS IN RELATION TO THE FOURTH CRITERION (TIME AND COST EFFECTIVENESS) (10 COMPARISONS)

Factor	EBM	SLM/SLS	SLA	WAAM	FDM	Priority vector (%)	Rank
EBM	1.00	2.00	1.00	1.00	5.00	27.30	2
SLM/SLA	1/5	1.00	3.00	1.00	7.00	28.90	1
SLA	1.00	1/3	1.00	2.00	4.00	20.90	3
WAAM	1.00	1.00	1/5	1.00	3.00	18.30	4
FDM	1/5	1/7	1/4	1/3	1.00	4.70	5
Sum	3.40	4.47	5.45	5.33	20.00	100.1	

From Table VIII, the principal Eigen value and the consistency ratio were calculated as 5.421 and 9.4% respectively. This implies that the weight allocation to the competing criteria and the pairwise comparison process were consistently carried out since the CR<10%.

The overall weights for the AM techniques based on the identified criteria are calculated as follows from Eq. [4]-[8]:

$$EBM = 48.10(31.00) + 38.70(39.80) + 41.10(22.90) + 27.30(6.40) = 4147.27$$

$$SLM/SLS = 22.30(31.00) + 27.40(39.80) + 8.20(22.90) + 28.90(6.40) = 2154.56$$

$$SLA = 8.90(31.00) + 19.40(39.80) + 22.10(22.90) + 20.90(6.40) = 1687.87$$

$$FDM = 7.80(31.00) + 10.30(39.80) + 11.60(22.90) + 4.70(6.40) = 947.46$$

$$WAAM = 12.90(31.00) + 4.20(39.80) + 16.80(22.90) + 18.30(6.40) = 1068.90$$

Figure 3 presents a bar chart that shows the comparative analysis and visualization of the overall weights of the AM techniques that can be employed for the manufacture of the brake disc based on the identified criteria. In the order of their ranking from the most feasible to the less feasible are: EDM, SLM/SLS, SLA, WAAM and FDM. This implies that when considering the manufacturing of brake disc via AM with the requirements of product quality functional requirements, optimal energy consumption and environmental friendliness as well as time and cost effectiveness of the manufacturing process, the EDM is the most suitable AM process based on the analytical hierarchy process selection demonstrated in this study.

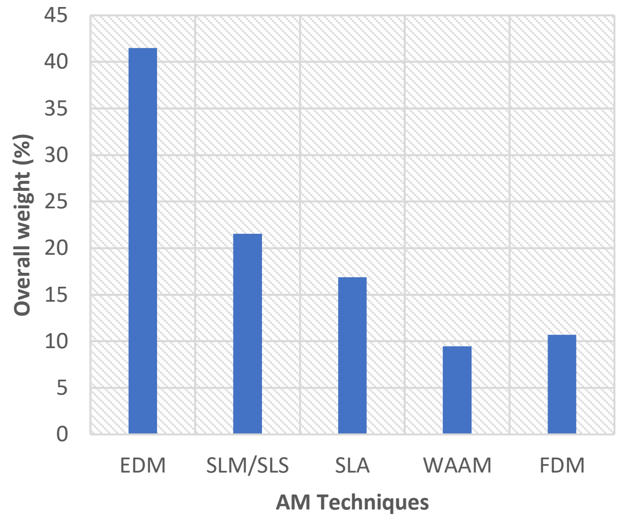

FIGURE 3 COMPARATIVE ANALYSIS AND VISUALISATION OF THE OVERALL WEIGHTS OF THE AM TECHNIQUES

CONCLUSION

This study aimed to highlight the importance of considering the user's needs and preferences in the design process, and how AM can facilitate needs in Product Service System (PSS). To achieve this, this study proposes an approach that considers the user's preference based on the Analytical Hierarchy Process (AHP) to select the feasible AM technology that reflects product preferable behavioural design requirements. The proposed AHP decision matrix is validated with a brake disc manufacturing requirements namely product quality, service and functional requirements, energy consumption as well as time and cost effectiveness using four AM techniques of EDM, SLM/SLS, SLA, WAAM and FDM. The results obtained demonstrated its alignment with the weights obtained from real-world scenarios. This approach is effective because the theory of inventive problem-solving is a design approach used in systematic analysis that generates innovative solutions for design problems. In conclusion, this study contributes to the understanding of how to integrate AM into the PSS design process using a user-centred approach. The study is limited to the identification of user's needs and preferences in the design process and the validation using the AHP for brake disc manufacturing.

It is recommended that manufacturing industries integrate the multi-criteria decision-making approach demonstrated in this study into their AM and part selection processes to provide a scientific and reliable basis for the selection processes. Future works can be on the comparative analysis of the AHP used and employ other multi-criteria decision-making approaches such as the Fuzzy Analytical Hierarchy Process.

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