Selection of filament holder design for the Learning Factory purposes using the multi-criteria decision-making method

***Amanda Aljinović Meštrović*[1], *Andrea Juzbašić*[1], *Nikola Gjeldum*[1] *and Andrej Bašić*[1]**

1) Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, 21000 Split, Croatia

Corresponding author: amaljino@fesb.hr

Original Scientific Paper

Abstract: The learning factory is a controlled environment that replicates the key features of industrial production systems, enabling education and research without the constraints of actual production. This environment allows for the resolution of specific problems that arise from the daily use of various production technologies. In this paper, the issue of selecting the most suitable filament holder with a mass of 5 kg for use in a learning factory environment is addressed, as the specified filament cannot be accommodated by the existing holder. Based on design guidelines for additive manufacturing, three different filament holder design alternatives are proposed. To select the most appropriate alternative, the analytical hierarchy process (AHP) method was applied. In evaluating the alternatives, five criteria were defined, covering functional, production, and usage aspects of the design: volume, reliability of use, assembly complexity, flexibility, and ease of use. The results of the AHP method showed that reliability of use has the greatest influence on decision-making, while assembly complexity is the least significant of the criteria considered. Based on the total priority values of the alternatives, Model 2 was identified as the most suitable solution. The proposed approach enables structured and transparent design selection.

Keywords: *filament holder; design for additive manufacturing; additive manufacturing; MCDM; AHP method*

1. Introduction

With the advent of the fourth industrial revolution, commonly known as Industry 4.0, a transformative manufacturing approach called additive manufacturing (AM) has been introduced [1]. Unlike conventional manufacturing processes, AM is more sustainable manufacturing process, producing three-dimensional (3D) components by applying material layer by layer starting from a digital model [2]. Due to its numerous advantages over traditional technologies, such as lower operating costs, fewer production steps, operational flexibility and the durable, high-strength properties of its components, this technology is attracting increasing attention in parts/product manufacturing. Notable manufacturers using AM include Siemens and Widex for producing hearing aid shells, and Boeing for manufacturing of some parts of the F-18 fighter jets [3]. AM technologies can be divided into powder-based, liquid-based or solid-based processes, depending on the raw material used. One of the most commonly used techniques within solid-based additive manufacturing, and in general, is Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF). This technology is very popular because it is affordable and supports a wide range of materials, making it suitable for a variety of applications, from prototyping to the production of functional parts. The Learning Factory (LF) at the University of Split is equipped with an FDM printer, the PRUSA i3 MK3S+. Through the learning factory concept, a real factory environment has been created, allowing students to work with actual industrial equipment and address real industrial problems during their education. In addition to training students, this environment is also ideal for training industrial employees and conducting various scientific research activities [4]. Since the Learning Factories strive for continuous progress and development as the main goal of the researchers and students working there, every challenge or obstacle is an opportunity to innovate and improve the existing process. One such challenge arose at

the Learning Factory, where the existing 5 kg filament cannot be used due to the lack of a suitable filament holder. Normally, filaments that are compatible with the printer's existing filament holder are used. However, in a recent project, a 5 kg filament was purchased that did not fit into the existing holder. This filament is shown in Figure 1.



Figure 1. *5 kg filament [5]*

To address the problem, a customized filament holder was designed and printed using an available 3D printer. Although many commercially available filament holder designs exist, the decision was made to create and print a holder in-house. This choice offers both economic and educational benefits. Economically, it uses existing resources, such as filament and parts already available in the Learning Factory. Educationally, it provides Learning Factory participants with opportunities to learn about multi-criteria decision-making methods, design principles for 3D printing, and to gain experience using CAD software and the 3D printing process. Additionally, designing a filament holder allows for a more personalized, customized, and cost-effective solution tailored to the user's specific needs.

This research aimed to identify the most suitable design for printing and implementation in the Learning Factory. Developing a customized filament holder typically requires evaluating multiple design alternatives that differ in functional and manufacturing constraints. To support the selection of the most appropriate option, a multi-criteria decision-making (MCDM) approach was adopted. By applying MCDM, the various design options are evaluated based on key criteria defined by the decision makers. This analysis enables the selection of the design that best meets the needs and requirements of users in the Learning Factory. The product selection workflow is shown in Figure 2.

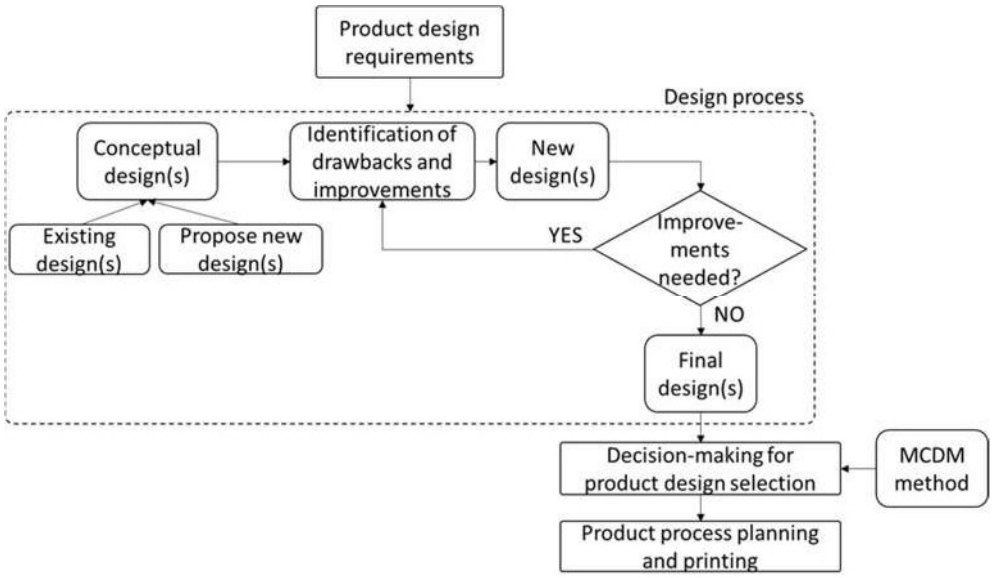


Figure 2. *Product selection workflow*

2. Additive manufacturing

Additive manufacturing is a technology in which 3D objects are created layer by layer from a 3D CAD models. In addition to the term additive manufacturing, terms such as 3D printing, rapid prototyping and rapid manufacturing are also used in the literature to describe this process [6]. The typical workflow for manufacturing products or parts using additive technology can be described in several steps. These steps are shown in Figure 3. The first step refers to the creation of the 3D geometry to be printed (3D model). In this step, 3D CAD software such as NX, SolidWorks and Catia can be used to create a virtual 3D model. Once the 3D model is defined, it is converted into a format understood by additive manufacturing machines, such as the STL file format. After conversion to the STL file format, the file is imported into slicer software (e.g., PRUSA Slicer) where the model is prepared for manufacturing. In the slicer software, the orientation and position of the part(s) in the build area are defined. The software breaks down the geometry of the 3D model into individual layers. For each layer, the geometric data and important machine parameters are defined and translated into production instructions (G-code generation) [7]. The G-code is transferred to the AM machine (e.g., an FDM printer), and the build process runs autonomously. Once the part is printed, it is removed from the build area. Post-processing is then carried out if necessary. After post-processing, the parts are inspected and tested. If necessary, adjustments can be made to the design of the part(s) based on feedback from inspection and testing. Finally, the printed parts can be used for their intended purpose.

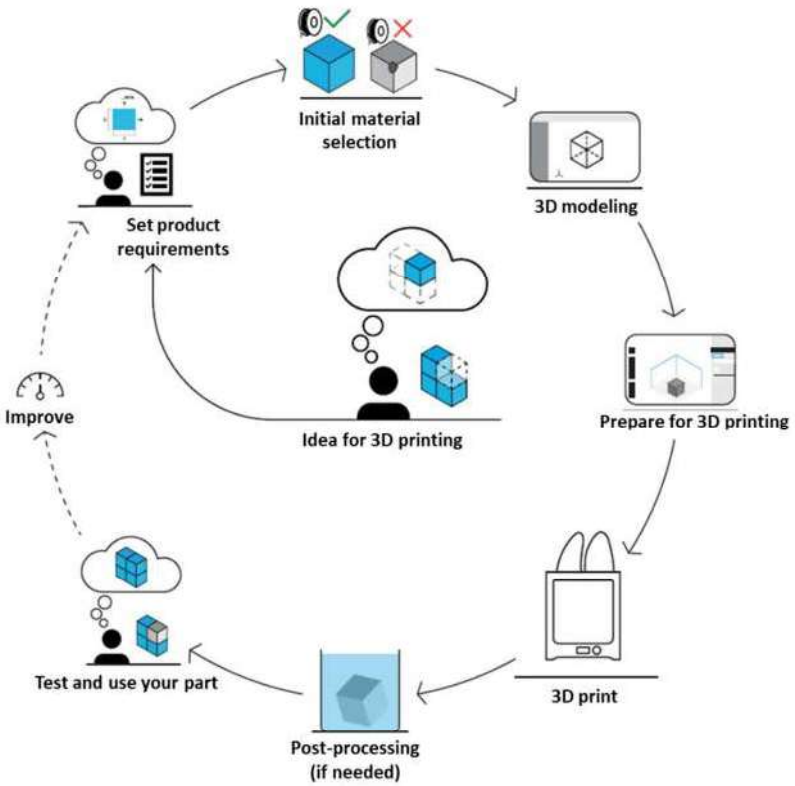


Figure 3. *Additive manufacturing workflow [8]*

3. Importance of multi-criteria decision making

Multi-criteria decision-making (MCDM) methods are valuable tools for decision makers selecting solutions to specific problems. They address the challenge of evaluating and ranking alternatives based on multiple, often conflicting, criteria. The general workflow of the MCDM process consists of several steps, as shown in Figure 4.

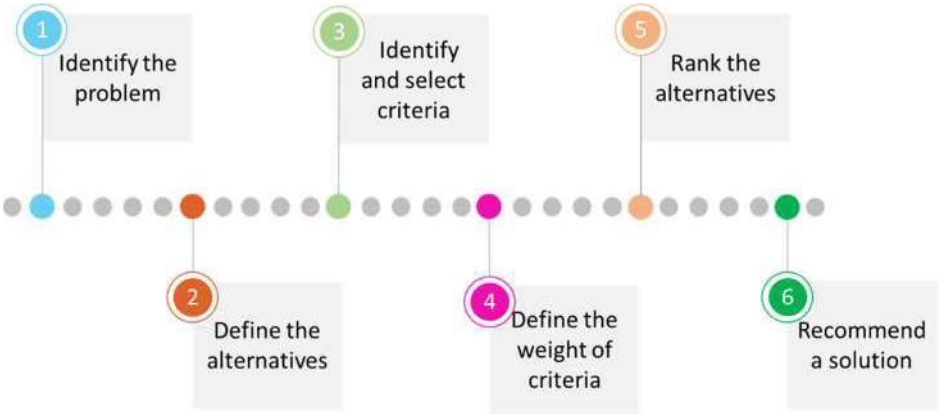


Figure 4. *General steps of the MCDM methods*

In this figure, the alternatives represent different possible solutions to the problem, the criteria are used to evaluate and compare the alternatives [9] and the weighting reflects the importance of each criterion for solving the problem, indicating the preferences of the decision makers. A wide range of MCDM methods has been proposed in the literature, differing in their theoretical foundations, required input types, and the nature of their results. The most commonly used methods for product design evaluation and their areas of application are listed in Table 1.

Table 1. *MCDM methods and their application in product design and development [10]*

Methods	**Area of application**	**Methods**	**Area of application**
Weighted Sum Method (WSM)	Structural optimization, product assessment, fund allocation	Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)	Technology forecasting, concept selection, competitive benchmarking, plant layout design
Multi-Attribute Utility Theory (MAUT)	Supplier selection, city planning, testing and robustness assessment	Elimination and Choice Translating Reality (ELECTRE)	Business policy and strategy, risk and financial management, facilities planning
Analytical Hierarchy Process (AHP)	Concept selection, buyers selection, customer needs selection, resource management	Goal Programming (GP)	Product planning, production planning, cost estimation
Analytical Network Process (ANP)	Concept selection and evaluation, supplier selection, material selection, site selection	Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)	Plant location selectin, concept selection, resource evaluation

However, there is no universal method that is equally successful in all areas. Therefore, it is challenging to determine which MCDM method is best suited to a particular problem. The choice of method depends on the decision maker's experience and the area of application. AHP is the most popular method for design evaluation, and according to the Scopus and Current Content databases, AHP is generally the most widely used MCDM method. Therefore, the multi-criteria design selection problem in this study is addressed using AHP method.

4. Methodology

Three filament holder designs were developed to represent different design concepts with varying levels of complexity, stability, and material consumption. Design alternatives were developed according to the design rules for 3D printing using the FDM methodology, as shown in Figure 5.

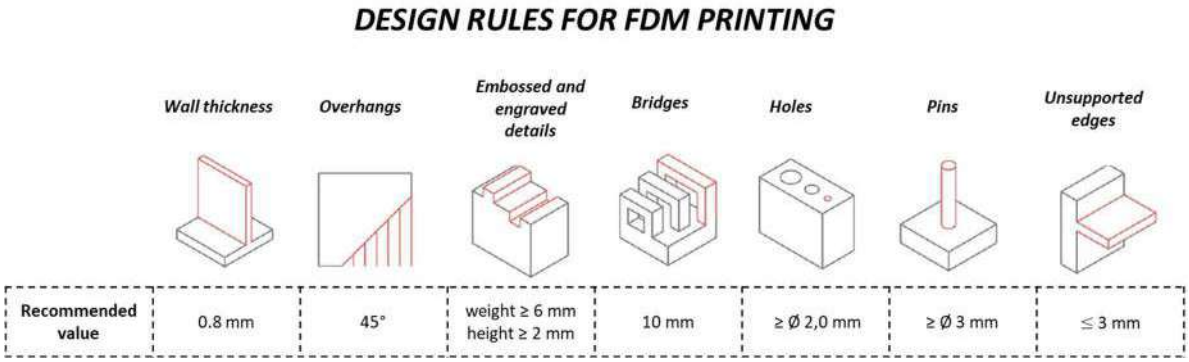


Figure 5. *Design rules for 3D printing [11]*

These three basic designs Model 1, Model 2 and Model 3 are shown in Figure 6 and were created using Siemens NX software. Model 1 is the initial design solution and features an adjustable width for the filament, achieved through a sliding side wall. This mechanism allows the insertion of filaments of various sizes and ensures stable positioning. Model 2 is based on the concept of the first model but has a simplified design. In this version, the filament is placed on U-slots attached to ball bearings, allowing smooth rotation during use. Model 3 has the largest volume among the presented solutions and was developed to increase stability when handling larger filaments. In this model, the filament is placed directly on a shaft that passes through its inner diameter. The shaft is fixed between the side walls and further stabilized by horizontal rods and nuts. Although the design is robust, its flexibility is limited, as the holder must adapt the shaft diameter to the filament's inner diameter, requiring additional adjustments in case of deviations.

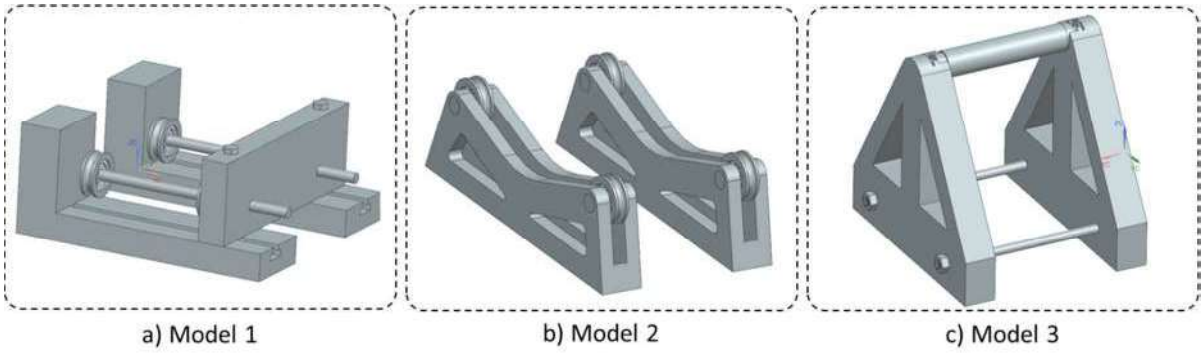


Figure 6. *Three alternatives of filament holder design*

In order to determine the most suitable filament holder alternative, five evaluation criteria were defined and used to assess the models. The criteria considered are:

- VOLUME (values from Siemens NX software) – this criterion enables a quantitative comparison of the models based on the amount of material required for production. It is assumed that a model with a larger total volume requires more material, provided that other 3D printing parameters (fill type, percentage, fill pattern, etc.) are identical for all models. As it is based on measurable data, this criterion is quantitative. The total volume of the models is shown in Table 2.

Table 2. *The total volume of the models*

	Model 1	Model 2	Model 3
Volume (mm^3)	802 182	344 396	2 295 046

- RELIABILITY IN USE – this criterion evaluates the safety and stability of the model during use.
- COMPLEXITY OF ASSEMBLY – this criterion assesses how complex it is to assemble the model after 3D printing.
- EASE OF USE – this criterion refers to how easy and quick it is to load filament into the holder. Intuitive operation and minimal steps required to change filament are advantageous when evaluating this criterion.
- FLEXIBILITY – this criterion is defined as the holder's ability to accommodate different filament sizes, especially regarding the width and inner diameter of the spool. Greater flexibility allows the use of a wider range of filaments without additional adjustments or redesign of components.

Of the defined criteria, volume is quantitative because it is taken directly from the CAD model and expressed as a numerical value. The other criteria are qualitative and based on the subjective assessment of the individuals with an engineering background and experience in additive manufacturing processes, ensuring a consistent and informed evaluation of the defined criteria. This approach is justified, as the AHP method is designed to integrate quantitative and qualitative criteria, with subjective assessments systematically processed and checked using the consistency index.

4.1. Application of the AHP method

In this paper, the AHP method was applied to select the most suitable filament holder. The AHP method structures the decision-making problem using a hierarchical model that includes the goal, criteria, and alternatives. The hierarchical model for the observed problem is shown in Figure 7. Criteria and alternatives are compared in pairs according to the Saaty scale of relative importance, which uses a measurement scale from 1 to 9. Based on these comparisons, the weights of the criteria and the local priorities of the alternatives are calculated. The final ranking of the alternatives is obtained by synthesizing the local priorities and the weights of the criteria. Because the AHP method relies on human assessments, it is important to check the consistency of these assessments. An acceptable result requires that the Consistency Ratio (CR) is less than or equal to 0.10. This index serves as a mathematical check of the logical consistency of the assessments, if its value exceeds 0.10, the weights and final results may be unreliable, and it is necessary to reconsider the comparisons entered [12].

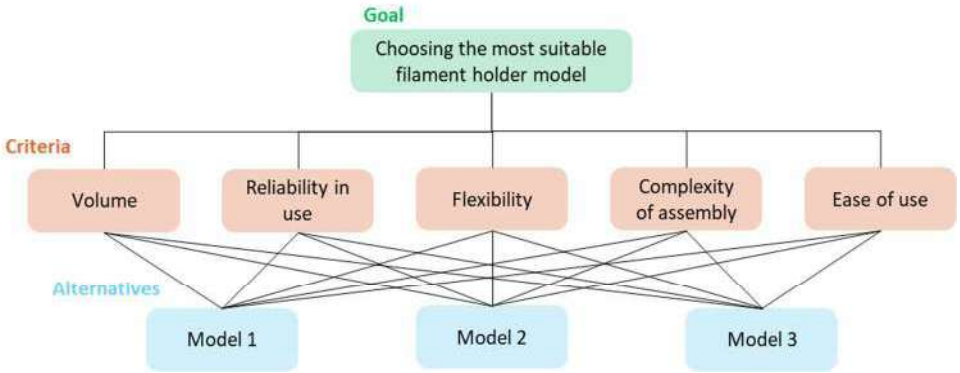


Figure 7. *Hierarchical model of the observed problem*

The online AHP calculator [13] was used to conduct the AHP method. The online tool was used only to support calculations, while the authors defined the decision problem structure and conducted all evaluations. After hierarchically structuring the problem, comparisons of criteria and comparisons of

the observed alternatives with respect to each criterion were performed. The pairwise comparison matrix of the criteria with respect to the overall goal is presented in Table 3, while the pairwise comparison matrices of alternatives with respect to different criteria are presented in Figure 8. It was found that all pairwise comparison matrices satisfy the consistency condition (CR ≤ 0.10).

Table 3. *Pairwise comparison matrix of criteria with respect to the goal*

	Volume	Reliability in use	Flexibility	Complexity of assembly	Ease of use
Volume		1/5	3	5	1/4
Reliability in use	5		5	9	3
Flexibility	1/3	1/5		1	1/5
Complexity of assembly	1/5	1/9	1		1/5
Ease of use	4	1/3	5	5	

a) Volume

	Model 1	Model 2	Model 3
Model 1		1/2	3
Model 2	2		7
Model 3	1/3	1/7	

b) Reliability in use

	Model 1	Model 2	Model 3
Model 1		1/6	1/4
Model 2	6		2
Model 3	4	1/2	

c) Flexibility

	Model 1	Model 2	Model 3
Model 1		1/5	3
Model 2	5		6
Model 3	1/3	1/6	

d) Complexity of assembly

	Model 1	Model 2	Model 3
Model 1		1/5	1/7
Model 2	5		1/3
Model 3	7	3	

e) Ease of use

	Model 1	Model 2	Model 3
Model 1		1/7	1/8
Model 2	7		1/3
Model 3	8	3	

Figure 8. *Pairwise comparison matrices of alternatives with respect to different criteria*

4.2. Results of the AHP analysis

The results of the AHP method implementation are presented in Figure 9.

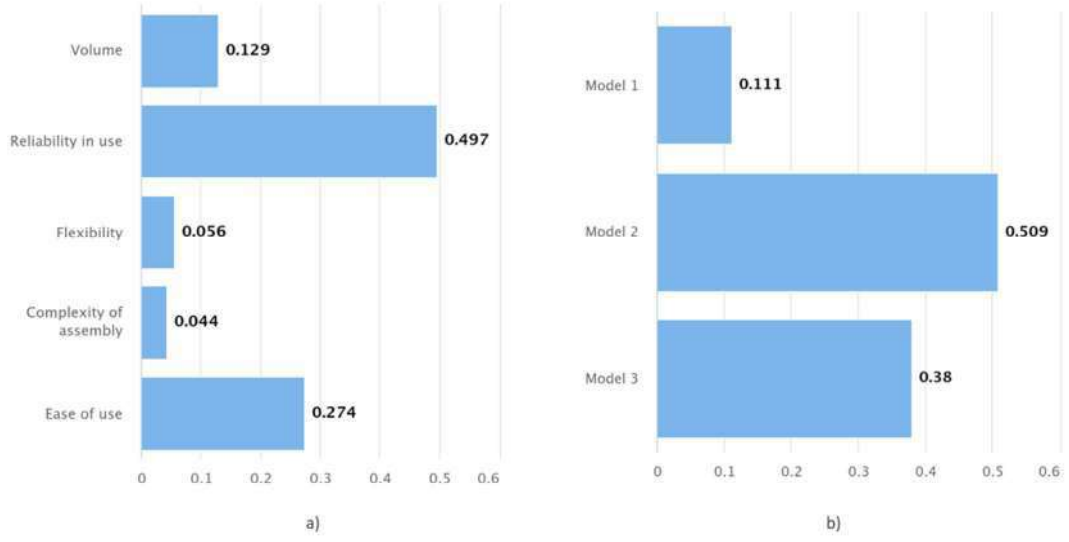


Figure 9. *The results of the implementation of the AHP method: a) Priorities of the criteria, b) Priorities of the alternatives with respect to goal*

As indicated in Figure 9 a), the most influential criterion in the decision-making process is reliability in use, emphasizing the importance of stable and safe handling of the filament during operation. In contrast, complexity of assembly is the least influential criterion, since assembly is performed only once, while operational performance is more important.
Based on the overall priority values of the alternatives, Figure 9 b), Model 2 was selected as the most suitable solution because of its low material consumption, simple assembly, and reliable operation, ensuring stable and efficient use.

5. Conclusion

This paper addresses the selection of the most suitable 5 kg filament holder for the LF environment. Following design guidelines for the AM process, three design alternatives for the filament holder were proposed and evaluated using the AHP method. Five criteria were defined for the evaluation, covering design, production, and use aspects. The results of the AHP method indicate that reliability in use is the most significant criterion for design selection, while complexity of assembly is the least significant. Based on the total priority values of the design alternatives, Model 2 was identified as the most appropriate solution, offering the best trade-off between low material consumption, assembly complexity, and reliability in use.
The main contribution of the paper is the structured formulation of the design selection problem in the context of FDM technology and the application of a multi-criteria decision-making method as a tool for objective comparison of design alternatives. The proposed methodology allows evaluation of design alternatives while considering several criteria of functionality, production, and application simultaneously. A significant contribution of the paper is the determination of the relative importance of individual criteria in the context of additive manufacturing in the learning factory environment, where reliability of application was identified as an important criterion in selecting auxiliary equipment.
While paper presents the application of the proposed methodology to the design of a filament holder, the methodology is not limited to this problem and may be used to address other design selection problems in additive manufacturing technology, especially in the early stages of product development when various alternative solutions and conditions must be considered. Thus, the paper contributes to the development of structured and transparent decision-making.
Although the results provide a reliable basis for selecting the optimal solution, a limitation of this research is the lack of experimental validation of the selected design under real operating conditions. Therefore, future research may include mechanical testing, performance evaluation, and long-term usability assessment of the selected filament holder in the LF environment. The proposed approach can also be improved by applying and comparing additional multi-criteria decision-making methods to further confirm the findings.

Acknowledgments

This work was supported by the European Union under the NextGenerationEU instrument, through the Recovery and Resilience Mechanism, within the institutional research project AIMTECH 4.5 (IP-UNIST-07), implemented by the Ministry of Science, Education and Youth of the Republic of Croatia.

References

[1] Dilberoglu, U.M., Gharehpapagh, B., Yaman, U., Dolen, M., 2017. The Role of Additive Manufacturing in the Era of Industry 4.0. Procedia Manufacturing, 11, 545–554. doi: 10.1016/j.promfg.2017.07.148

[2] Agrawal, R., Vinodh, S., 2019. State of art review on sustainable additive manufacturing. Rapid Prototyping Journal, 25 (6), 1045–1060. doi: 10.1108/RPJ-04-2018-0085

[3] Gibson, I., Rosen, D., Stucker, B., Khorasani, M., 2021. Additive manufacturing technologies, Springer, Cham.

[4] Abele, E., Metternich, J., Tisch, M., Kreß, A., 2024. Learning Factories, Featuring New Concepts, Guidelines, Worldwide Best-Practice Examples, Springer, Cham.

[5] FacilanTM C8 Filament. https://www.3d4makers.com/products/facilan-c8-filament?_pos=1&_sid=30fb8b41e&_ss=r (accessed 25 February 2026).

[6] Abdulhameed, O., Al-Ahmari, A., Ameen, W., Mian, S.H., 2019. Additive manufacturing: Challenges, trends, and applications. Advances in Mechanical Engineering, 11, 1–27. doi:10.1177/1687814018822880

[7] Vaneker, T., Bernard, A., Moroni, G., Gibson, I., Zhang, Y., 2020. Design for additive manufacturing: Framework and methodology. CIRP Annals, 69 (2), 578–599. doi: 10.1016/j.cirp.2020.05.006

[8] Ultimaker guide – How to design for FFF 3D printing. https://louisville.edu/amist/amist-print-farm/ultimaker-guide-on-how-to-design-for-fff-3d-printing (accessed 25 February 2025).

[9] Taherdoost, H., Madanchian, M., 2023. Multi-criteria decision making (MCDM) methods and concepts. Encyclopedia, 3 (1), 77–87. doi: 10.3390/encyclopedia3010006

[10] Kumar, P., Tiwari, A., 2021. MCDM-Based Decision Support System for Product Design and Development. In: Design for Tomorrow – Proceedings of ICoRD 2021, Springer, 575–584. doi: 10.1007/978-981-16-0119-4_46

[11] Redwood, B., Schöffer, F., Garret, B., 2017. The 3D Printing Handbook: Technologies, Design and Applications, 3D Hubs B.V., Amsterdam.

[12] Saaty, T.L., 1990. How to make a decision: The Analytic Hierarchy Process. European Journal of Operational Research, 48 (1), 9–26

[13] AHP Software. https://onlineoutput.com/ahp-software/ (accessed 23 March 2025).