The American Journal of Applied Sciences

ISSN 2689-0992 | Open Access

TYPE Original Research
PAGE NO. 32-43
DOI 10.37547/tajas/Volume07Issue10-03

Check for updates

Evaluation of 3D Printing Performance in Mechanical Manufacturing: A Comparative Study of Cost, Quality, and Time in Precision Gear Production

Dheyaa Abdulameer Shaiyah

Huwaiza Affairs Department, Misan Oil Company, Misan, Republic of Iraq.

OPEN ACCESS

SUBMITED 14 September 2025
ACCEPTED 22 September 2025
PUBLISHED 05 October 2025
VOLUME Vol.07 Issue 10 2025

CITATION
Dheyaa Abdulameer Shaiyah. (2025). Evaluation of 3D Printing Performance in Mechanical Manufacturing: A Comparative Study of Cost, Quality, and Time in Precision Gear Production. The American Journal of Applied Sciences, 7(10), 32–43.
https://doi.org/10.37547/tajas/Volume07Issue10-03

Abstract

Production and manufacturing processes are witnessing a significant increase in the reliance on 3D printers in this field, especially in complex and rare forms. The aim of this study is to demonstrate the capability and efficiency of a 3D printer in the production of unique and complex spare parts. A small damaged gear (a damaged spare part for the coffee machine) was selected as a case study due to the difficulty of obtaining such a spare part. Reverse engineering was used to take the necessary measurements of the gear and redraw it using the SolidWorks program, and then convert it to the printer's program and print it. A Creality Ender 3 Pro printer and polylactic acid (PLA) were used for the purpose of gear printing, and the printing time took about 4 hours. The measurements of the printed piece showed a great match as the accuracy reached in the range of ±0.15mm. The results of the comparison also showed that the cost of printing the gear is estimated at $1, while the cost of producing the same gear ranges from (10-25) dollars by traditional methods such as CNC milling or machining, while the molds are less expensive but require the purchase of large quantities (+1000), which contradicts the goal of the study and increases the cost significantly. Laboratory tests have also proven the efficiency of the material after printing, as good mechanical properties have been obtained and suitable for the intended purpose. Finally, the study concluded that the use of a 3D printer is an excellent and cheap solution for the

purpose of making spare parts, especially unique and rare.

Keywords: Production, Manufacturing, 3D printer, Gear, Spare part, CNC Milling, and Machining

1. Introduction

The roots of three-dimensional printing date back to the early eighties, when the first 3D printing technology was developed in 1981 by Harold Cohen, who used a method known as "thermal deposition" [1]. However, the paradigm shift in this technology came when Chuck Hull patented Stereolithography (SLA) in 1984, a method that relies on the use of lasers to harden liquid resin, paving the way for wider applications in manufacturing. Over the years, 3D printing technologies have evolved to include a variety of methods such as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Binder Jetting, improving accuracy, speed and cost efficiency [2]. The first applications and how they evolved to include multiple fields Initially, the main applications of three-dimensional printing were limited to the creation of prototypes in the fields of engineering and design. As technology has evolved, applications have begun to encompass multiple areas such as: Medicine: Three-dimensional printing was used in the manufacture of prostheses and anatomical models, which helped doctors plan surgeries. Engineering: Advances in 3D printing have made it possible to produce complex spare parts at a lower cost and shorter time. Space: Space agencies such as NASA have begun using three-dimensional printing to manufacture spare parts for spacecraft, facilitating the maintenance of equipment in space. Fashion: The use of three-dimensional printing in the design of clothing and accessories has spread, allowing designers to innovate in new forms.

Three-dimensional printing 3DP, or additive manufacturing, is defined as the process of transforming a digital model into a physical object by adding layers of material. This digital model is created using computer-aided design (CAD) software or by scanning real objects [3]. The object is designed using CAD software, where the dimensions and shape are determined. It divides data into two-dimensional layers, making it easier to print [4]. A 3D printer is used to print an object by adding layers of material (such as plastic, metal, or ceramic) one on top of the other until the final object is formed. The resulting object may require additional finishing operations such as sanding or painting [5]. Bogue (2013) presented an introduction to three-dimensional printing technology and its applications. He discussed how this technology has changed the manufacturing landscape and opens up new horizons for personalized production and custom manufacturing [6]. Schniederjans (2017) discussed the factors affecting the adoption of three-dimensional printing techniques in manufacturing. The research used the theory of the spread of innovations to analyze how senior management perceptions affect the speed of adoption of these technologies in companies [7].

Wu et al., (2018) addressed quality and quality control issues in 3D printing by reviewing past work and current practices. The research discussed quality control techniques used at different stages of the product life cycle, and reviews how the quality of three-dimensional printed products can be improved through techniques such as cause and effect analysis [8]. Shahrubudin et al., (2019) examined the types of 3D printing technologies and their applications in industry. It highlighted how 3D printing can be used to customize production and reduce waste, and discusses the materials used in these processes [9]. Srinivasan et al., (2021) provided a comprehensive overview of three-dimensional printing techniques, materials used, and their applications in the aircraft and automotive industries. The research explored how 3D printing can improve efficiency and reduce costs in manufacturing processes [10]. Wakiru et al., (2024) studied the integration of remanufactured and triple-printed parts in improving asset maintenance. He emphasizes that 3D printed parts provide local solutions for replacement parts, especially when access to parts is intermittent [11]. Richert et al., (2024) addressed surface quality as a factor influencing the functionality of products manufactured with metal and 3D printing technologies. It is used in the production of parts, tools, and molds, with the market forecast to grow from $20.81 billion in 2022 to $22.66 billion in 2024 [12]. Abdelkader et al., (2024) offered a comprehensive view of 3D ceramic printing and its applications. Custom manufacturing of jewelry and fashion accessories facilitates and provides flexibility in mechanical properties through the use of polymers and metals in 3D printing [13]. Sala et al., (2025) explored the prospects of assembly manufacturing in the industry, indicating that the market size reached $3.6 billion in 2022. The research focuses on improvements in the production of spare parts as one of the main axes for the development of 3D printing technologies in advanced industrial environments [14]. Choudhuri et al., (2025) provide a comprehensive review of 3D printing applications in the automotive and EV industry. It highlights how 3D printing enables the production of custom parts for older vehicles, overcoming the challenges of traditional manufacturing [15]. Kantaros et al., (2025) explored the role of 3D printing in the development of automated manufacturing systems through a critical review of the literature with case study analysis, focusing on its role in boosting production and heavy machinery [16]. Rojek et al., (2025) explored emerging applications of machine learning in 3D printing. It aims to improve the mechanical properties of partially recycled materials in 3D printing, opening up new horizons for the development of the technology [17]. Balloni et al., (2025) analyzed the impact of assembly manufacturing on supply chain management. It indicates significant growth that began in 2021 and 2022, with the focus being that spare parts production is a key topic in 3D printing applications [18]. Yeshiwas et al., (2025) provided a comprehensive review of the assembly manufacturing assessment, also known as 3D printing. It discusses the mechanical properties of FDM printed parts and explores recent advances in the field [19]. These researches confirmed recent trends in the use of 3D printing for mechanical manufacturing and parts production, with a focus on: cost and time savings of up to 95% time savings, flexibility in production and custom-made manufacturing, advanced industrial applications in automotive and aviation, environmental sustainability and green manufacturing, and the integration of smart technologies such as machine learning and automation.

3D printing has radically changed the way products are manufactured. It eliminated the need for many traditional processes, reducing the time and costs associated with production. Complex objects can now be produced in less time and with fewer resources, allowing manufacturers to offer customized products that better meet customer needs.

The objectives of the research are summarized as follows: Evaluation of 3D printing capability for precision gear manufacturing, comparing quality with traditional methods, cost and time analysis, and determining the best transactions for printing.

2. Methodology

2.1 Problem Description

The research problem is as follows:

- The presence of a machine that has a broken gear and cannot be operated.
- Lack of spare parts to replace the gear or the possibility of repairing it.
- The high cost of replacing or buying a new machine.
- The gear can be ordered from suppliers in China, but it is required to order in large quantities and at a high cost, and it requires a manufacturing and shipping time of one to two months.

Therefore, the need to manufacture a small gear with precise specifications has emerged, and one of the most important challenges in traditional methods (cost, time, complexity), as well as accuracy and quality requirements, has emerged.

2.2. Materials and Equipment

The printer used in this study is the Creality Ender 3 Pro (Fig. 1), which is considered one of the most economical and reliable 3D printers in its price category. This printer costs around $200, making it a suitable choice for use in small academic and industrial environments.

Fig. 1 Creality Ender 3 Pro 3D printer.

Polylactic Acid (PLA) was used for printing the gear. The material exhibits a tensile strength of 50-70 MPa, providing acceptable mechanical resistance for light and moderate engineering applications. One of the most important advantages of PLA is that it is environmentally friendly and biodegradable, as it is extracted from renewable natural sources such as cornstarch and sugarcane. This makes it an environmentally sustainable option compared to traditional petroleum-derived plastics, which contribute to reducing the environmental impact of manufacturing processes.

Fig. 2 PLA material.

2.3.Measuring and Modelling

The dimensions of the gear were measured as shown in Fig.3, where the dimensions were obtained using the vernier and ruler, as in the following Table 1.

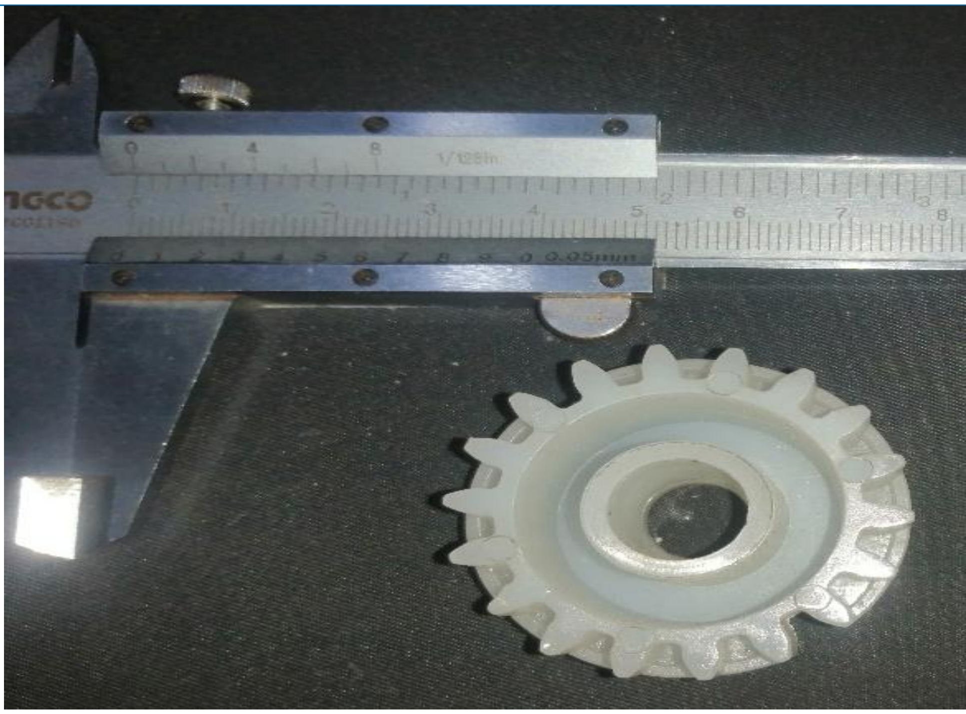


Fig. 3 Measuring the gear dimensions.

The reverse engineering was used to redraw the gear employing the Solidworks program, where the equation tool was used to draw the gear dimension based on the module, pressure angle, and number of teeth as in Fig.4 The final gear sample is shown in Fig.5.

Table 1 Gear Measured Dimensions.

Item	Value
Outer Diameter	40 mm
Pressure Angle	20°
Number of Teeth	18
Module	0.72 mm
Face Width	20 mm
Bore Diameter	10 mm

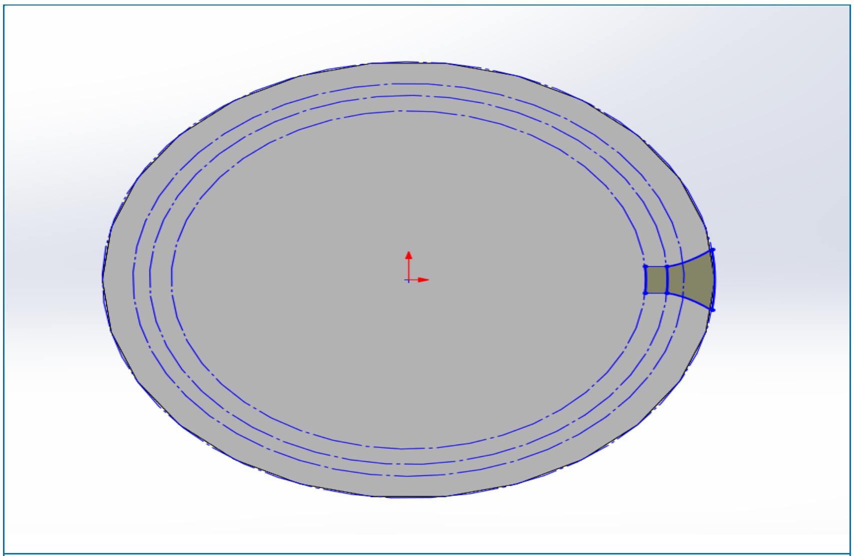


Fig. 4 Gear modelling using equation tool.

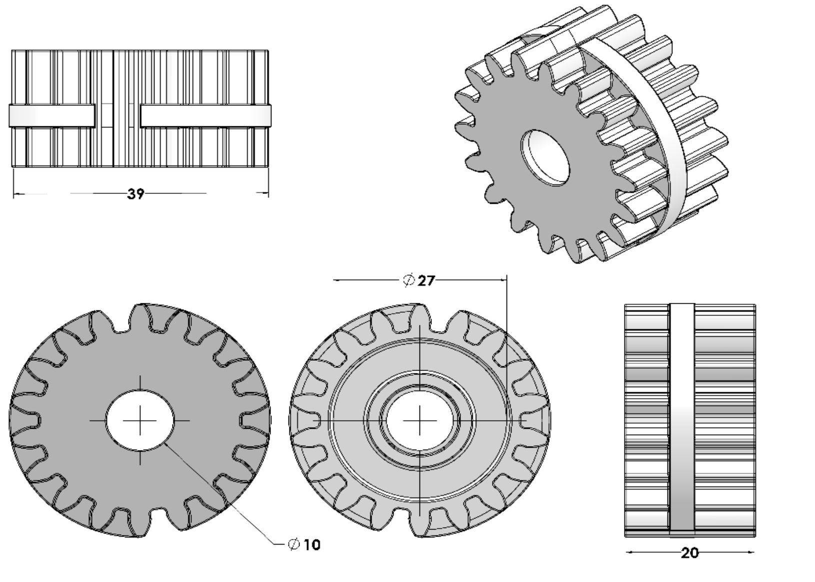


Fig. 5 The final gear sample.

3. Gear Manufacturing

3.1. Preparations stage

The preparation stage involved several basic steps to ensure the quality of the print. The Ultimaker Cura software was used to convert the 3D model into a printing instruction (G-code) using the "Super Quality - 0.12mm" profile. Key settings included: 0.24mm layer thickness with 0.12mm thick first layer for better adhesion, 30mm/s print speed with reduced wall speed to 15mm/s for high pinion shaping accuracy. The printing temperature is set at 225°C and the platform temperature at 95°C to ensure perfect melting and strong adhesion. Use the Raft system as an auxiliary base with an additional 8mm margin for improved stability. Full cooling (100%) of layer 4 and above is activated to prevent thermal distortion, with an estimated total printing time of 4 hours and consumption of approximately 15 grams of PLA.

3.2. Gear Printing Stage

The printing process began with the platform and nozzle being heated to the set temperatures, followed by the automatic leveling of the platform using the BL Touch sensor to ensure uniform distribution of layers. The basic Raft layer was first printed to provide a stable base, and then the actual model began printing with a layer thickness of 0.24 mm. During printing, the process was visually monitored to ensure the quality of the layers and the adhesion of the material. The printing process lasted for about 4 hours with the consumption of 15 grams of PLA.

3.3. After Printing Stage

After the printing process was completed, the printed gear was left for around 10 minutes to cool, then it was removed using a sharp machine to avoid causing damage to the gear. The piece has been thoroughly cleaned and any excess or deformities have been removed. The final dimensions were measured using a vernier, where it was found that a dimensional accuracy of 0.15 mm was obtained.

4. Results and Discussions

4.1. 3D Printing Results

In this research, the 3D printer was used for the purpose of manufacturing a spare part for a specific machine, which is a small gear for the purpose of demonstrating the importance and capability of 3D printers in manufacturing and forming processes, especially in unique and rare parts that do not require large quantities. The following results were obtained as shown in Table 2.

Table 2 Manufacturing Results.

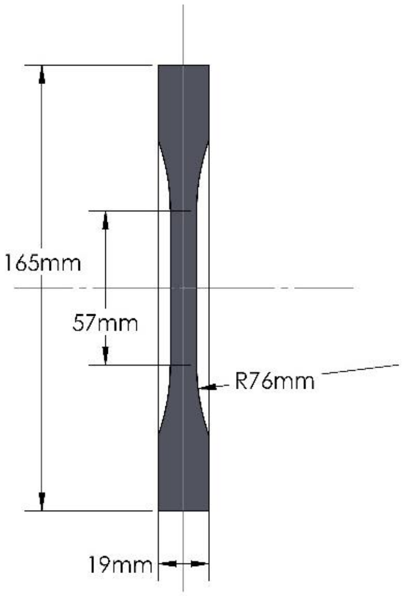
Result	Value
Printing Time (hour)	4
Amount of consumable material (g)	15
Material cost ($)	0.6
Total Cost ($)	1
Dimensional Accuracy (mm)	±0.15

The results shown in Table 2 show the high efficiency of 3D printing in the manufacture of specialized parts. The micro-gear printing process took only 4 hours, which is a relatively short time compared to traditional methods that may require days to manufacture a similar piece, especially when special molds or molding tools are needed. In economic terms, the results showed exceptional cost efficiency, with the consumption of the material amounting to only 15 grams for $0.6 for raw materials, and the total cost of $1, including operating and energy costs. This makes 3D printing the perfect choice for limited production and rare pieces that don't justify huge traditional manufacturing investments. It achieved a dimension accuracy of ±0.15mm, which is excellent accuracy for normal mechanical applications and matches the requirements of most functional parts. This level of precision confirms the technology's ability to produce usable components rather than just prototypes, opening up wide applications in the maintenance and immediate repair of equipment. These results confirm that 3D printing represents an ideal solution to modern manufacturing challenges, especially in the field of rare and specialized parts, as it offers high flexibility and speed of execution with low cost and acceptable accuracy for industrial applications. The final product is shown in Fig.6.

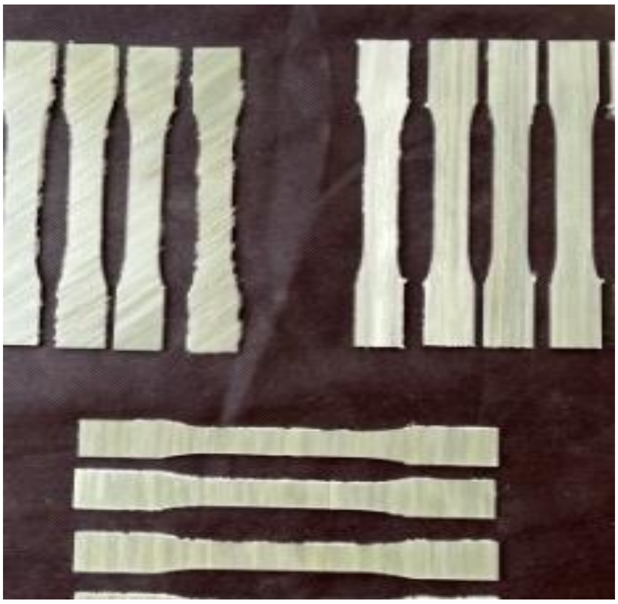
Fig. 6 ***Old and Final Product.***

4.2. Tensile and Hardness Test

The tensile test was conducted to verify the part's mechanical properties after the manufacturing process (3D Printing). The test was implemented according to ASTM D638-14 [20] as in Fig.7. The dimensions of the tensile test sample are presented in Fig.7a, according to the related standard, while the test sample (i.e., 3D printed) is shown in Fig.7b. All these tests were carried out in the laboratories of the Mechanical Department, College of Engineering, University of Technology, as shown in Fig.8.



صورة



(a)	(b)

Fig. 7 a) Tensile test sample parameters, b) the printed sample.

صورة

Fig. 8 Tensile Test Machine.

The hardness test was also carried out according to ASTM D785 [21] utilizing a calibrated Shore-D durometer. The standard sample is a flat specimen with a minimum thickness of 6 mm, a minimum area of 6 cm^2, and a minimum width of 25 mm. The sample's surfaces must be flat, free from dust and grease, and conditioned to standard atmospheric conditions before testing. The hardness test was also conducted in the laboratories of the Technology University, as shown in Fig.9.

Fig. 9 Hardness Test.

The results are presented in Table 3, where a good agreement was achieved with the raw PLA material.

Table 3 Tensile and Hardness Test Results.

Maximum Tensile Stress (MPa)	Strain at maximum Stress %	Yong's Modulus (MPa)	Hardness (Shore D)
38	5	3450	54

Maximum tensile stress 38 MPa: This is an average value for PLA plastics, which is suitable for bearing medium loads. Elongation when tensile 5%: It indicates that the material is relatively brittle, i.e. it does not expand much before breaking. This is common with PLA, which is characterized by rigidity rather than flexibility. Young's coefficient of 3450 MPa: Gives an idea of the material's hardness and resistance to deformation under loads. This is a decent value for small gears operating at low to medium speeds, but it is lower than some engineering materials, such as Nylon or Acetal. Shore Hardness D = 54: Medium value, indicating a medium hardness that enables it to withstand pressure and partial wear, but is lower than the high-performance engineering plastics commonly used in heavy gears. The results are close to typical PLA values, indicating that the print was of good quality, but slightly below the upper limit for hardness and tolerance. The material used (PLA) is suitable for small coffee machine gears or applications that do not require high load or high temperatures. Rigidity and Young's modulus are suitable for gears that move at low and medium speeds.

4.3. Comparative Economic Analysis

Cost vs. Traditional Methods: Comparative economic analysis between 3D printing and traditional methods (Table 4) shows substantial differences in cost structure. In traditional manufacturing, making a similar gear requires high initial setup costs that include mold design ($200-500), production line setup, and specialized labor costs, making the total cost per piece between $15-25. In contrast, 3D printing achieved a total cost of just $1, saving up to 95% of the traditional cost. These huge savings are due to the absence of the need for special molds or tools, the limited consumption of raw materials (15 grams vs. 50-100 grams in traditional methods due to waste), as well as the reduction of labor and operating costs. In terms of time, 3D printing significantly outperformed 4 hours compared to 3-7 days for traditional methods (including setup and manufacturing time) (Fig.10). This translates to an 18x higher delivery speed, which reduces equipment downtime and improves maintenance efficiency. This comparison shows that 3D printing has a strong competitive advantage in the manufacture of limited quantity parts, especially for rare or discontinued parts, as it combines economic savings with speed of execution.

Table 4 Results of Manufacturing Methods Comparison.

Manufacturing Method pieces	Cost/Piece	Manufacturing Time	Minimum Quantity
3D Printing	$1.00	4 Hours	1 Piece
CNC Milling	$15-25	2-3 Hours	1 Piece
Injection molding	$0.50	minutes	1000+
Machining	$10-20	1-2 Hours	1 Piece

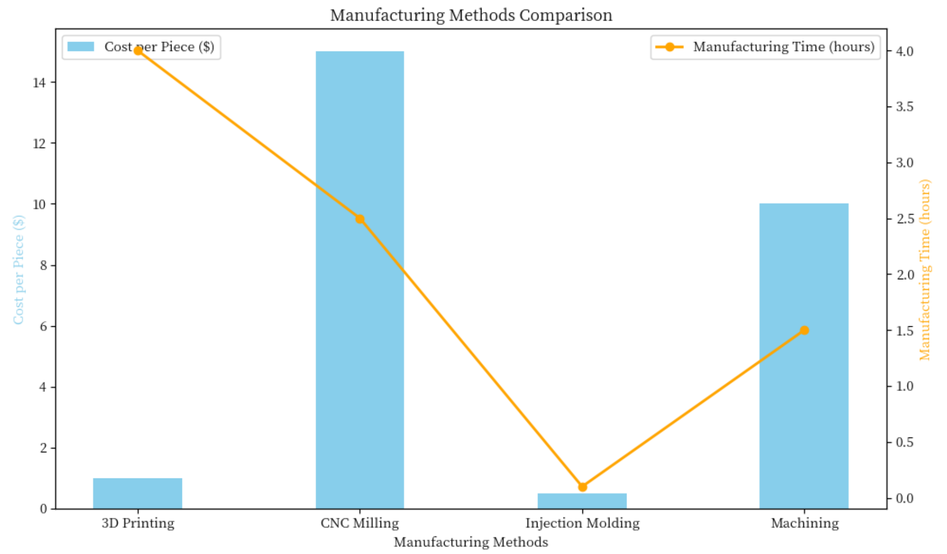


Fig. 10 Manufacturing Methods Comparison.

Comparative economic analysis has demonstrated the clear superiority of 3D printing over traditional methods in the manufacture of quantitative parts. 3D printing achieved cost savings of up to 95% ($1 vs. $15-25) and 18x faster production (4 hours vs. 3-7 days). These results confirm that the technology represents the best economic and technical solution for the manufacture of rare and specialized spare parts, which opens up wide prospects for its application in industries that rely on fast and efficient maintenance.

5. Conclusions and Recommendations

Based on the above results as well as the comparative analysis of the different manufacturing methods, the following can be deduced:

1. Cost and economic feasibility: 3D printing is the best option in terms of cost for limited quantity production at a cost of only $1 per piece Injection molding achieves the lowest cost per unit ($0.50) but requires large production volumes starting from 1000 pieces CNC milling and machining require a larger financial investment ($10-25 per piece)

2. Time efficiency: Injection molding shows the highest time efficiency for mass production (minutes per piece) 3D printing requires more time (4 hours) but eliminates the need for setup and preparation time CNC milling and machining provide a reasonable balance between time and quality

3. Flexibility in production: 3D printing has high flexibility that allows for the production of a single piece when needed. Injection molding is not suitable for individual production or small quantity required spare parts.

4. The Mechanical Test showed that the material used (PLA) is suitable for small coffee machine gears or applications that do not require high load or high temperatures.

The following recommendations of the current study:

1. For Institutions and Companies: Adopting 3D printing as an essential solution for the production of spare parts and prototypes due to its optimal balance between cost and flexibility. Developing a hybrid production strategy that combines 3D printing for small quantities and injection molding for mass production

2. For practical applications: The use of 3D printing in the aerospace and automotive industry to produce rare or discontinued spare parts. Applying this technology in the medical sector to produce custom devices and instruments.

3. For Technical Investment: Investing in the development of 3D printing technologies to improve speed and quality. Build a distributed production network based on 3D printing to reduce transportation and storage costs.

4. Strategic Recommendation: 3D printing is the perfect solution for the future of manufacturing, especially in the era of the digital economy and on-demand production, combining cost-effectiveness, operational flexibility, and environmental sustainability.

Author Contributions: The authors contributed to all parts of the current study.

Funding: This study received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. A. Su and S. J. Al'Aref, "History of 3D Printing," in *3D Printing Applications in Cardiovascular Medicine*, Elsevier, 2018, pp. 1–10. doi: 10.1016/B978-0-12-803917-5.00001-8.
2. I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies*. New York, NY: Springer New York, 2015. doi: 10.1007/978-1-4939-2113-3.
3. C. W. Hull, "The Birth of 3D Printing," *Research-Technology Management*, vol. 58, no. 6, pp. 25–30, Nov. 2015, doi: 10.5437/08956308X5806067.
4. B. Evans, *Practical 3D printers: The science and art of 3D printing*. Apress, 2012.
5. J. Hiemenz, "3D printing with FDM: How it Works," *Stratasys Inc*, vol. 1, pp. 1–5, 2011.
6. R. Bogue, "3D printing: the dawn of a new era in manufacturing?," *Assembly Automation*, vol. 33, no. 4, pp. 307–311, Sep. 2013, doi: 10.1108/AA-06-2013-055.
7. D. G. Schniederjans, "Adoption of 3D-printing technologies in manufacturing: A survey analysis," *Int J Prod Econ*, vol. 183, pp. 287–298, Jan. 2017, doi: 10.1016/j.ijpe.2016.11.008.
8. H.-C. Wu and T.-C. T. Chen, "Quality control issues in 3D-printing manufacturing: a review," *Rapid Prototyp J*, vol. 24, no. 3, pp. 607–614, Apr. 2018, doi: 10.1108/RPJ-02-2017-0031.
9. N. Shahrubudin, T. C. Lee, and R. Ramlan, "An Overview on 3D Printing Technology: Technological, Materials, and Applications," *Procedia Manuf*, vol. 35, pp. 1286–1296, 2019, doi: 10.1016/j.promfg.2019.06.089.
10. D. Srinivasan *et al.*, "3D Printing Manufacturing Techniques, Materials, and Applications: An Overview," *Advances in Materials Science and Engineering*, vol. 2021, no. 1, Jan. 2021, doi: 10.1155/2021/5756563.
11. J. Wakiru and P. Muchiri, "Integrating Remanufactured and 3D Parts in Asset Maintenance Improvement," 2024, pp. 547–559. doi: 10.1007/978-3-031-52649-7_43.
12. M. Richert, M. Dudek, and D. Sala, "Surface Quality as a Factor Affecting the Functionality of Products Manufactured with Metal and 3D Printing Technologies," *Materials*, vol. 17, no. 21, p. 5371, Nov. 2024, doi: 10.3390/ma17215371.
13. M. Abdelkader, S. Petrik, D. Nestler, and M. Fijalkowski, "Ceramics 3D Printing: A Comprehensive Overview and Applications, with Brief Insights into Industry and Market," *Ceramics*, vol. 7, no. 1, pp. 68–85, Jan. 2024, doi: 10.3390/ceramics7010006.
14. D. Sala and M. Richert, "Perspectives of Additive Manufacturing in 5.0 Industry," *Materials*, vol. 18, no. 2, p. 429, Jan. 2025, doi: 10.3390/ma18020429.
15. B. Choudhuri, M. F. Uddin, and R. Sen, "Review on 3D printing technology in automotive industry and electric vehicle," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, May 2025, doi: 10.1177/09544070251337273.
16. A. Kantaros, C. Drosos, M. Papoutsidakis, E. Pallis, and T. Ganetsos, "The Role of 3D Printing in Advancing Automated Manufacturing Systems: Opportunities and Challenges," *Automation*, vol. 6, no. 2, p. 21, May 2025, doi: 10.3390/automation6020021.
17. I. Rojek, D. Mikołajewski, M. Kempiński, K. Galas, and A. Piszcz, "Emerging Applications of Machine

Learning in 3D Printing," *Applied Sciences*, vol. 15, no. 4, p. 1781, Feb. 2025, doi: 10.3390/app15041781.

18. A. Balloni, L. Monferdini, and E. Bottani, "The Impact of Additive Manufacturing on Supply Chain Management: Trends, Challenges and Future Directions," *Procedia Comput Sci*, vol. 253, pp. 2961–2970, 2025, doi: 10.1016/j.procs.2025.02.020.

19. T. A. Yeshiwas, A. B. Tiruneh, and M. A. Sisay, "A review article on the assessment of additive manufacturing," *Journal of Materials Science: Materials in Engineering*, vol. 20, no. 1, p. 85, Jul. 2025, doi: 10.1186/s40712-025-00306-8.

20. "Test Method for Tensile Properties of Plastics," Dec. 15, 2014, *ASTM International, West Conshohocken, PA*. doi: 10.1520/D0638-14.

21. "Test Method for Rockwell Hardness of Plastics and Electrical Insulating Materials," May 10, 1998, *ASTM International, West Conshohocken, PA*. doi: 10.1520/D0785-98E01.