Original Research

Adapting Machining Strategies for the Sustainable Fabrication of Titanium Implants Using AHP and PROMETHEE

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Abstract

This study proposes a sustainability-oriented optimization framework for the manufacturing of titanium ASTM F67 implants, integrating economic, environmental, and social indicators through a combined Analytic Hierarchy Process (AHP) and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE II) approach. Two non-conventional machining technologies wire electrical discharge machining (WEDM) and abrasive waterjet cutting are analyzed, combined with milling and drilling operations to simulate 84 distinct manufacturing routes under varying demand scenarios (low, regular, high). Sustainability indicators, including energy consumption, CO_2 equivalent emissions, raw material utilization (titanium volume), and tool waste (carbide), are quantified and normalized. These are integrated alongside cost and operational safety metrics into the multicriteria decision-making framework. Energy consumption differs by up to 70% between the most and least efficient routes, while titanium utilization varies by 25%, directly impacting material costs and environmental footprint. The framework enables flexible weighting of criteria, accommodating different market or policy priorities. Results demonstrate that waterjet cutting combined with milling reduces energy consumption by up to 40% and titanium waste by 25% compared to WEDM routes under regular demand conditions, making it the most sustainable choice in such scenarios. Conversely, WEDM routes outperform in high-demand scenarios, achieving up to 35% higher productivity, despite elevated energy use. The framework offers a robust and adaptable decision-support tool, applicable not only to the biomedical sector but also scalable to other industries seeking to balance productivity and sustainability goals. This study delivers practical guidance for manufacturers and insights for policymakers aiming to promote sustainable manufacturing practices.

Keywords - Sustainable manufacturing; Titanium implants; AHP-PROMETHEE; Multicriteria decision-making (MCDM)

INTRODUCTION

The development of new materials for biomedical applications has garnered significant interest over the past decades. The growing number of studies in this field is justified, as the most visible outcome is an improvement in quality of life, which contributes to increased life expectancy—a reflection, in general, of the population's health and well-being conditions[1]–[4]. Degenerative diseases and the increase in life expectancy, which is a global trend, make the scientific and technological development of biomaterials even more important[5]. Currently, given this context, there is a substantial effort to produce raw materials for the fabrication of implant devices, particularly orthopedic ones[6]. Therefore, the optimization of manufacturing processes is necessary, as the final cost of metallic implants, especially those made from titanium-based materials, remains high. This study specifically addresses the challenges of machining commercially pure titanium ASTM F67, a material widely used in biomedical implants due to its superior biocompatibility. The research aims to develop a multicriteria decision-making framework that optimizes the selection of machining routes by integrating economic, environmental, and social indicators, ensuring both process efficiency and sustainability in implant manufacturing.

In recent years, sustainable production practices have gained paramount importance due to the increased environmental awareness and the urgent need to meet sustainable development goals[7]. Manufacturing industries, especially those dealing with high-performance materials such as titanium, play a crucial role in this transformation. Titanium and its alloys are widely used in various industries, including aerospace, medical, and automotive, due to their superior properties, such as high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility[8]–[13]. However, machining titanium alloys, particularly ASTM F67, presents significant challenges due to its low thermal conductivity and high chemical reactivity, which lead to rapid tool wear and high cutting temperatures[14], [15].

In this regard, one point to be noted is the issues inherent to processing. According to Huang (2018), failures in engineering components generally occur on the surface due to the high probability of high stress and surface defects. If compressive residual stress is introduced near the surface, an improvement in fatigue conditions and abrasion resistance can be achieved. Consequently, various methods to improve mechanical properties have been enhanced and developed to induce residual compressive stress. These methods include shot peening, laser peening, low-plasticity polishing, and deep rolling. Compared to other methods, the deep rolling process can generate a thicker layer of residual compressive stress.

On the other hand, metallic materials treated with MSE (Mechanical Surface Enhancement) exhibit higher shear and tensile strength at elevated temperatures than the untreated material. However, their ductility decreases. To measure this effect of cold work, some studies involving grain refinement or annealing have been conducted.

More specifically, machining processes are used for manufacturing specific products that, in some cases, require dimensional precision (e.g., certain types of gears and screws) and also for finishing purposes (adjusting geometries, dimensions, and surface finish) in semi-finished parts (Kiminami, 2013).

Furthermore, according to Kiminami (2013), machining is a manufacturing process in which a cutting tool is used to remove material from a solid so that the remaining part has the desired shape. The main machining processes are turning, drilling, and milling. Machining is applied to a wide variety of materials, generating any regular geometry, such as flat surfaces, cylinders, and round holes. It is often used as a secondary or finishing process when the part has been produced by casting, plastic forming, or powder metallurgy.

Li and collaborators (2017) state that in modern manufacturing processes, reducing energy consumption is one of the most relevant and challenging issues due to the global energy crisis and climate change. In milling processes, only 14.8% of energy consumption is utilized by the cutting tool, making process improvement a focus for both academia and industry. Researchers have studied the relationship between cutting parameters and energy consumption.

Additionally, production costs decrease with the increase in cutting speed up to a certain point, but after that, they rise again. Regarding feed rate, costs consistently decrease as the feed rate increases. As shown in Figure 10, costs do not always decrease with an increase in cutting speed, but they do decrease with increased cutting depth. Therefore, it can be concluded that when the minimization criterion is energy consumption, cutting speed should be higher than the value calculated for cost optimization. In some cases, feed rate ranges may exceed those recommended for the tool. The minimum production cost can be achieved with the minimum number of passes in facing operations where more than one pass is required to complete the process.

According to Arriaza (2017), machining accounts for a significant portion of energy consumption. Developing processes with improved energy efficiency will significantly reduce the energy consumption of manufacturing companies. Thus, it is crucial to consider energy efficiency without sacrificing productivity. Energy savings can reach up to 40% with an optimized selection of cutting parameters, cutting tools, and tool paths. This demonstrates that substantial improvements can be achieved by balancing the factors involved in machining processes without the need for investments in new materials or machinery.

Accordingly, titanium-manufactured products are machined after annealing (approximately 35 HRC), as their original hardness exceeds 40 HRC. The high temperatures generated at the interface between the chip and the tool, along with titanium's low thermal conductivity and high chemical reactivity, lead to premature tool wear. Tool wear is characterized by the synergy of crater wear, which accelerates flank wear. Additionally, titanium's low modulus of elasticity causes deformation problems, impacting cutting forces during the machining of thin parts. This results in poor surface finish and low precision during milling operations.

Regarding the main machining operations required for the implant manufacturing industry, cutting processes, such as water jet cutting and wire electrical discharge machining (WEDM), stand out. According to Bhattacharyya (2020), the water jet cutting process is an advanced mechanical energy process based on the principle of directing high-speed water against the workpiece to be cut. The velocity of the water jet exceeds 1400 m/s. When the high-speed jet hits a small area of the workpiece, a high level of deformation is induced, exceeding the material's resistance. During cutting, material is removed from the workpiece following the same principle as the erosion mechanism caused by particle impacts.

On the other hand, in the wire electrical discharge machining process, the mechanical behavior of the wire is extremely complex. This is due to the occurrence of impacts between the wire and the workpiece, which exhibit a highly stochastic behavior, with various forces acting on the wire in different magnitudes and directions, none of which are constant (Bhattacharyya, 2020). The WEDM process is further complicated by a combination of factors, including fluctuations in current and voltage, random ionic migration, interactions between successive discharges, and the presence of gas and particles in the narrow machining zone.

Moreover, the main forces acting along the wire include gas forces formed by the erosion mechanism, hydraulic forces, electrostatic forces, and electrodynamic forces. Consequently, it is very difficult to quantitatively estimate these forces. However, researchers have been able to experimentally determine the forces acting perpendicularly during the process. All these mentioned forces, along with axial tension applied to the wire, are responsible for the wire's vibration and bending in the reverse direction of the cut when discrete impacts occur between the wire and the workpiece.

In the machining of titanium and its alloys, as well as nickel alloys, many combined machining techniques are being studied to improve process productivity and reduce damage induced by the machining process. These techniques include high-pressure fluid application during machining (HPAM), thermal enhanced machining (TEM), and vibration-assisted machining (VAM), which uses ultrasonic frequency with low amplitude for excitation or low frequency with high amplitude. These techniques show promising results in turning and drilling but are challenging to apply in milling processes. Cryogenic machining, utilizing CO2 or liquid nitrogen for strong cooling in the cutting area instead of fluid emulsions, also shows potential.

Several comparative studies demonstrate that conventional machining methods typically result in higher material waste, greater tool wear, and increased energy consumption, especially when processing difficult-to-machine materials like titanium alloys [16]. Furthermore, additive manufacturing (AM), particularly laser-based techniques such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), offers benefits in terms of material utilization and complex geometries, but often at the cost of higher energy intensity and surface finishing requirements compared to subtractive processes [16], [17]. In contrast, hybrid processes, combining additive and subtractive techniques, have shown potential to optimize material usage, improve surface finish, and reduce production times, especially for complex or repair-oriented applications [18].

However, for the specific precision requirements and surface integrity needed in biomedical titanium implants, wire EDM and waterjet cutting remain among the most suitable non-conventional methods, balancing dimensional accuracy, material integrity, and sustainability considerations. Future studies could extend this comparative framework to include cryogenic-assisted machining, hybrid additive-subtractive processes, or laser cutting, especially considering their varied energy profiles and environmental impacts [16], [19].

Despite advances in machining technology and sustainability assessment methods, significant gaps still remain. Most of the existing studies focus on individual aspects, such as tool wear or environmental impact, but fail to integrate them into a comprehensive framework to optimize sustainability indicators in titanium machining[20]–[22]. Additionally, there is limited research on the application of MCDA to simultaneously address the environmental, economic, and social dimensions in titanium machining processes, particularly for ASTM F67 titanium[21], [23]–[25]. This gap calls for the development of a decision support system that can holistically evaluate and optimize sustainability indicators in titanium machining. Addressing these gaps is crucial for advancing the sustainability of titanium machining processes. A comprehensive decision support system will allow manufacturers to optimize their operations by considering multiple sustainability indicators. This holistic approach can lead to significant environmental benefits, such as reduced emissions and energy consumption, while also enhancing economic efficiency and social responsibility. The development of such a system will not only improve the sustainability of titanium machining but also set a precedent for other high-performance material industries. Therefore, the main focus of this research is the development and validation of a decision support system based on multicriteria analysis to optimize environmental, economic, and social sustainability in the machining of ASTM F67 titanium. By evaluating 84 manufacturing routes under different production demand scenarios, the proposed framework provides quantitative insights for selecting the most sustainable machining strategies for titanium implants. This approach contributes directly to the optimization of titanium machining processes, bridging the gap between academic analysis and industrial application, and offering a decision-support tool adaptable to real-world manufacturing environments.

METHODOLOGY

I. Selection of Manufacturing Techniques and Parameters

For the study, hypotheses were raised regarding the production roadmap with different raw material cutting processes, machining strategies and parameters, clamping systems, and tool types. The main variables of the implant's production process are profile cutting, machining of threaded holes, milling of cavities, and milling of the external profile, where the final surface finish is applied to the product. The milling process uses various tools, such as roughing and finishing mills, for example.

To collect data, the product was manufactured using four distinct types of processes. The variables between the processes are: Raw material geometry; Cutting machine; Clamping system; Cutting parameters for the milling process; Cutting parameters for the drilling process. As shown in Figure 1, there are several ways to produce the product. However, to optimize sustainability parameters, it is necessary to find which combination holds the best choice.

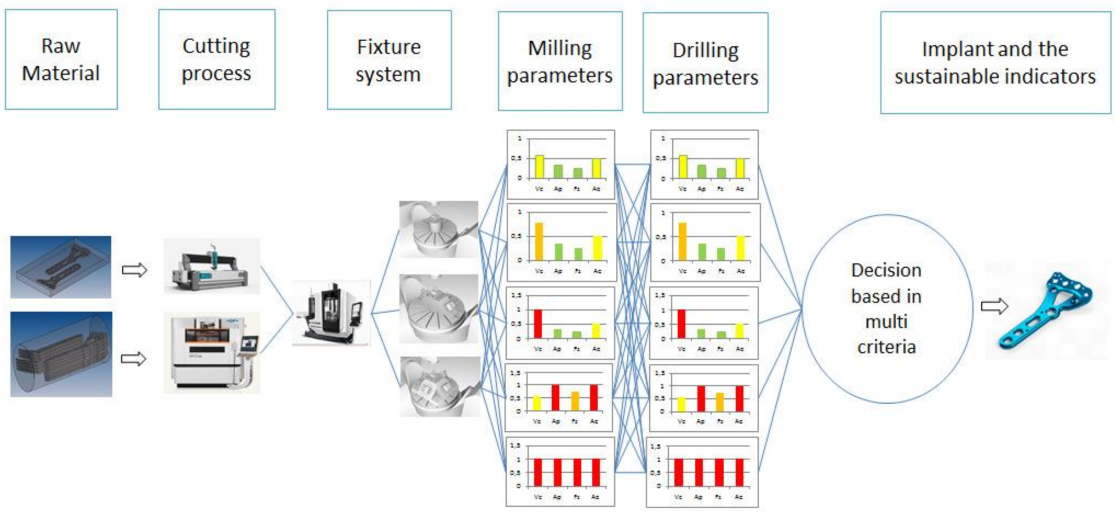


FIGURE 1
PROCESS FLOWCHART ROUTING BASED IN THIS RESEARCH (SOURCE: AUTHORS OWN WORK)

The manufacturing of the implant begins with the cutting process of the raw material, which can be done in two distinct ways: by water jet or wire electrical discharge machining (EDM). The water jet cutting process offers lower precision and requires subsequent milling of the cut face. However, when compared to the wire EDM process, the water jet cutting performs the operation in less time. In the wire EDM process, the final finish of the product can be obtained without the need for subsequent profile milling, and the material utilization is considerably superior[26], [27].

The water jet cutting process used was based on a commonly utilized cutting machine, the Flow Mach500. This equipment performs cuts with precision according to the drawn profile, as it features a modern architecture with advanced cutting technology, a smooth motion system that produces precise and agile parts. The finish obtained on the cut for sheets with this equipment can vary from 1 to 25 mm in thickness. As presented in Figure 1a, in the water jet cutting process, a sheet with a thickness 2 mm greater than the product's thickness is used, and it does not provide a final finish to the product, requiring a subsequent milling operation on all faces of the piece, which is carried out at the machining center. The sheet cutting is performed at an average speed of 15 mm/min. The advantage of using water jet cutting is its agility and superior productivity compared to the wire EDM process[26], [27].

For the cutting process using the Electrical Discharge Machining (EDM) technique, the machine model used was based on the GF CUT E350 model. The cut is made using a brass wire with a diameter of 0.25 mm, and the cutting process requires only one pass, with no need for a re-pass operation for surface finishing. The EDM cutting process allows for a distance of 0.4 mm between the pieces, leading to considerable material savings compared to water jet cutting, where a greater spacing between pieces is required to ensure a stable process. For this alternative, the implant profile was cut from bars, and based on the piece's profile and the bar's diameter, the best possible material utilization was achieved. Details can be observed in Figure 1b. The piece cutting is performed at an average speed of 3.7 mm/min, varying according to the thickness being cut. The finish obtained from EDM cutting eliminates the need for machining operations, which allows for a reduction in the time spent using the 5-axis machining center, thereby increasing the system's productivity compared to other processes.

The grouping of pieces in the bar, as shown in Figure 1b, along with the use of a rotary axis in the axial direction of the raw material, allows for the automated cutting of all pieces in the bar. With the equipment's autonomy and cutting efficiency, the reduction in material consumption and labor becomes evident.

In the milling and drilling process, the final geometric and dimensional shape of the product is obtained. This stage must necessarily be carried out on a machine with five movement axes due to the geometric complexity defined in the product's design. The equipment used as the standard for process study is the DMG – Mori CMX 50U machining center. Machining is performed using carbide tools with geometry and sizes according to the product's technical specifications.

The evaluation parameters of the production process were carried out considering sustainability indicators in the social, economic, and environmental fields. In the social field, operational training time is measured, and this parameter seeks to verify the difficulty of operating the equipment, considering the tool setup and adjustments during production. The second indicator is worker safety, which considers manual intervention in the production process. The third social indicator is labor time per piece produced. In the economic field, machining time, cutting time, total production cost, production capacity, and initial investment are measured, taking into account the number of vices and tools to be acquired. In the environmental field, the indicators are electrical energy consumption, the volume of ASTM F67 Gr.2 titanium raw material, and the amount of tungsten carbide waste used, as this is the material used to manufacture the cutting tools.

In the machining operation, it is necessary to select the cutting parameters that best adapt to the weight given to each criterion being measured. The estimated time to replace a damaged tool is 15 minutes; however, due to the ability to change tools without needing to stop production, the tool change time is not accounted for in the machining time calculation, serving only for labor usage time estimation.

The base calculation for the amount of material (chips) to be removed per piece in the milling process is 9 cm^3 when the piece is cut using the water jet and 1.1 cm^3 when the cutting process is performed on the wire EDM equipment.

The machining process requires the selection of cutting parameters such as depth of cut (Ap), width of cut (Ae), cutting speed (Vc), and feed per tooth (Fz), which must be within the range established by the tool manufacturer. To obtain an initial result, the Coroplus Tool Guide application from the tool manufacturer Sandvik Coromant was used. After entering the process data, the tool RA390-16T08-11L with the R390-11-T3-O8M-MM-2040 insert was suggested. The recommended cutting parameters were a cutting speed of 36.3 m/min, a feed of 0.135 mm/rev, a width of cut (Ae) of 13.33 mm, and a depth of cut (Ap) of 10 mm. However, the depth of cut was adjusted to 3 mm due to the product's geometry. Upon completion of the platform input, the expected tool life is 30 minutes.

II. Evaluation Criteria for Manufacturing Scenarios

For the creation of scenarios, the minimum and maximum ranges of all parameters involved in the milling and drilling processes were analyzed, as shown in Table I. Similar to the milling process, the tool selected for drilling was the solid carbide CoroDrill 860 drill 860.1-0430-013A1-SM 1210 to perform the operation. According to the CoroPlus Tool Guide platform(Sandvik CoroPlus®)[28], a cutting speed of 20.5 m/min and a feed of 0.08 mm/rev were suggested as the initial application, and the platform predicts a tool life of 45 minutes. The same criteria were applied to the drilling process, defining the ranges for cutting parameters and various test combinations as shown in Table I. For the drilling process, only two types of process parameters were analyzed: cutting speed and feed per revolution.

To assemble the production alternatives, ranges of application were defined for each parameter. For the cutting speed in the milling process using the R390-11-T3-O8M-MM-2040 insert, where the minimum range is 25 m/min and the maximum is 43 m/min, five different ranges were simulated along with the other process parameters. Table I presents all the simulation ranges for the milling and drilling processes. These parameter ranges, together with the type of cutting process and clamping system used in the process, form the alternatives that will be simulated later for ordering.

TABLE I
INVESTIGATION OF TOOL LIFE IN DIFFERENT CUTTING CONDITIONS.

Simulation tool life RA390-016O16L-11L					**Simulation tool life 860.1-0430-013A1-SM 1210**		
Vc(m/min)	Ap(mm)	Ae(mm)	Fz(mm)	Tool life (min)	Vc(m/min)	Fz(mm)	Tool life (min)
28	1	8	0.05	59	15	0.065	85
27	1	16	0.05	60	15	0.075	71
26	1	16	0.1	60	15	0.08	65
35	2	16	0.15	26	15	0.09	56
35	2	16	0.2	24	15	0.095	53
35	3	16	0.2	24	18	0.065	69
35	3	16	0.2	24	18	0.07	63
43	3	16	0.2	15	18	0.075	57
43	3	16	0.2	15	18	0.085	49
25	3	16	0.2	60	18	0.095	43
30	3	16	0.2	35	22	0.065	53
27	1	16	0.05	60	22	0.075	44
26	1	16	0.1	60	22	0.085	38
35	2	16	0.15	26	22	0.095	33
35	2	16	0.2	24	26	0.065	43
30	3	16	0.2	35	26	0.075	36
30	3	16	0.2	35	26	0.085	31
25	3	16	0.2	60	26	0.09	29
25	3	16	0.2	60	26	0.095	27

An important factor influencing the productivity of the machining process is the clamping system. In the production of parts where the product's size is small compared to the available volume of the equipment performing the machining, one can opt for clamping systems that allow the production of multiple parts per work cycle. The longer the equipment's work cycle, the greater the machine's autonomy, meaning that by the end of each work shift, the number of parts that the clamping system allows to be held in the equipment can be autonomously manufactured. However, the study of the clamping system, as well as the number of parts to be produced, should be sized according to the project budget and the necessary production demand.

In the design of the clamping system, the possibility of producing the product in three scenarios was analyzed. In the first and simplest scenario, a base and a vise are used to manufacture one piece per cycle. In this option, the goal is to work with a low investment and less autonomous production cycles. In the second scenario, the clamping system is designed to produce three pieces per cycle. In this case, the investment in the system is higher, but it offers greater productivity and more machine autonomy. In the third and most productive scenario, the possibility of producing five pieces per cycle is evaluated. In this case, the clamping system design utilizes the full volume of the equipment, maximizing the machine's capacity while considering its movement limitations. This scenario requires a more substantial investment, but it provides the highest degree of productivity and autonomy.

The loading and unloading time of the machine is a factor influenced by the number of pieces clamped per cycle. The operator spends three minutes per piece for clamping with the system designed for 1 piece per cycle, 2.5 minutes per piece for clamping with the system designed for 3 pieces per cycle, and 2 minutes per piece for clamping with the system designed for 5 pieces per cycle. These values are used for determining production capacity, labor utilization, production costs, energy consumption, and initial investment.

III. Sustainability Indicators for Evaluating the Production Process

The sustainability indicators represent the performance of the production process, and for each alternative, it is necessary to calculate them. As previously described, the indicators are subdivided into three categories: social, economic, and environmental. The scheme presented in Table II outlines all the indicators, as well as the objective and function of each.

TABLE II
SUSTAINABILITY INDICATORS: ECONOMIC, SOCIAL AND ENVIRONMENTAL.

Criteria		Objective
Economic	Machining time	Minimize
	Cutting time (Raw material)	Minimize
	Total cost	Minimize
	Production capacity	Maximize
	Investiment	Minimize
Social	Operational training time	Minimize
	Operator security	Maximize
	Labor time	Minimize
Environmental	Volume of titanium	Minimize
	Carbide waste	Minimize
	Consumption of energy	Minimize

The sustainability indicators are calculated according to the following equations[29]:

$$TU = TF + Tf + TT \quad (1)$$

$$TOC = \frac{PC}{V} \quad (2)$$

$$CP = (TU/60) * (CM + CHM) + (CF * \left(\frac{TU}{VFC}\right) + CMP \quad (3)$$

$$CDP = \left(\frac{60}{TU} * 0.8 * HT\right) + PA \quad (4)$$

$$II = CSF + CFM + CIMP \quad (5)$$

$$TMO = \left(\frac{TU}{VFC} * TTF\right) + TT \quad (6)$$

$$CE = CEM * \frac{TU}{60} \quad (7)$$

$$VU = \frac{C\ x\ L\ x\ A}{1000} \tag{8}$$

$$VU = \frac{(\text{Ø}/2)^2\ x\ LB}{QP}\ /1000 \tag{9}$$

$$QR = \frac{TU}{VFC} *\ PF \tag{10}$$

$$TTR = TTF + TTCU + TTMC \tag{11}$$

Where: TU = Machining time (minutes); TF = Milling time (minutes); Tf = Drilling time (minutes); TT = Part change time (minutes); TOC = Cutting operation time (minutes); PC = Cutting perimeter (mm); V = Cutting speed (mm/min); CP = Production cost ($); CM = Labor cost ($); CHM = Machine hour cost ($); CF = Cutting tool cost ($); VFC = Cutting tool life (minutes); CMP = Raw material cost ($); CDP = Daily production capacity (pieces); HT = Working hours per day; PA = Clamping system capacity for autonomous production; II = Initial investment ($); CSF = Clamping system cost ($); CFM = Estimated monthly tool consumption ($); CIMP = Initial cost for raw material purchase; TMO = Labor time per piece (minutes); TTF = Tool change time (minutes); CE = Energy consumption (KW/h); CEM = Machine energy consumption (KW/h); VU = Volume of material used to manufacture a piece (cm³); C = Sheet cutting length (mm); L = Sheet cutting width (mm); A = Sheet thickness (mm); Ø = Diameter of the bar used for cutting; LB = Length of the bar used in the cutting pattern; QP = Number of parts to be cut with the bar length LB; QR = Amount of carbide waste generated in the process per piece (Kg); PF = Weight of the cutting tool (Kg); TTR = Operational training time (hours); TTF = Clamping training time (minutes); TTCU = Machining center training time (minutes); TTMC = Cutting machine training time (minutes).

The sustainability indicators are calculated according to each of the items listed in Table II. The machining time (TU) of the implant is measured in equation 1. This indicator serves as the basis for the calculation of other indicators, which is why it is calculated first. The total machining time is essentially the sum of the drilling time, milling time, and tool change times. The tool change time is related to the process parameters, as higher parameters will result in faster execution of the part; however, tool life tends to be shorter. If the cutting parameters are excessively high, the total machining time may be reduced due to the frequent tool changes that will occur during the process.

The second sustainability indicator is the cutting operation time (TOC), which is described in equation 2. As described, the process can be performed on either a water jet cutting machine or a wire electrical discharge machine (EDM). The calculation is derived from kinematics, where time is the distance traveled by the object divided by the average speed of the object, which in this case is the cutting device of the equipment. This indicator makes it possible to calculate productivity, cutting production capacity, and production flow.

The cost calculation is performed by adding the machining time in hours (TU/60) to the equipment's hourly cost along with the machine operator's cost. The cost of cutting tools, which is the cost of the tool divided by the number of pieces that the tool produces, is also added, along with the cost of raw material, which in this case has two cutting process options. This indicator is essential for maintaining cost balance, ensuring that it does not exceed values where the company's profit could be compromised, especially when aiming to meet high demand.

The equipment's daily production capacity is measured by equation 3. In this case, the part of the equation (60/TU) x 0.8 represents the equipment's hourly production with an 80% efficiency rate. This efficiency value is based on practical daily observations, where the machine's effective time and actual production are measured. The hourly production value is then multiplied by the working hours of the day, which is added to the autonomous production that can be performed at the end of the day. This calculation assumes that at the end of the shift, a new production cycle will begin with the number of parts that the clamping system described in Figure 1c allows. For example, if a clamping system with 5 vices is acquired, 5 additional parts can be produced per day.

The calculation of the sustainability indicator related to the initial investment to be made in the process project is given by equation 4. In this case, it includes the cost of the clamping system, that is, the number of vices plus the coupling system (1), the monthly consumption of cutting tools, which in this case will be one month of production (2), and the cost of raw material for one month of production (3). Options 2 and 3 take into account the capacity of the production system, and the cost of raw material considers the cutting process. If the clamping system is for wire EDM, the purchase of bars is considered, and if water jet cutting is used, sheets with the thickness specified in the project are considered.

Labor is calculated using equation 6, which is the sum of the time for changing cutting tools and the time for changing the part.The calculation of energy consumption in the production process is carried out using equation 7, where the energy consumption of the equipment is multiplied by the machining time per hour. The raw material consumption in the production process varies according to the type of machine used for cutting, using equation 8 for water jet cutting or equation 9 for wire EDM cutting.

The sustainability indicator described in equation 10 calculates the amount of carbide waste, which is the material from which the cutting tool is made, used in the manufacturing of a part. The calculation divides the machining time of the part by the tool's life and multiplies it by the weight of the cutting tool. Once again, this equation relates to the cutting speed, feed, and cutting depths that are applied.

To enhance the environmental assessment, the energy consumption for each machining process was calculated in kilowatt-hours by multiplying the machining time by the nominal power of the respective machine tools, as provided in the manufacturers' technical specifications. Furthermore, to translate energy consumption into environmental impact, we adopted the carbon intensity factor of electricity grid, which is 0.084 kg CO_2 per kWh according to literature [30]–[33]. This allowed for the estimation of CO_2 equivalent emissions associated with each production route, providing a clearer perspective on their environmental footprint.

In addition to energy consumption, the environmental indicators incorporated titanium consumption (expressed in cubic centimeters) and carbide waste (measured in grams), representing material use and tool degradation, respectively. These indicators were normalized between 0 and 1 to facilitate comparative analysis across different routes within the multicriteria decision-making framework. This methodology ensures a balanced evaluation of the environmental performance of each machining scenario, aligning with best practices in sustainable manufacturing assessments.

IV. Selection of Manufacturing Parameters Based on AHP-PROMETHEE

The AHP-PROMETHEE methodology was technically implemented using a custom algorithm developed in Python. The Analytical Hierarchy Process (AHP) was applied to generate the weights for the economic, social, and environmental criteria. Pairwise comparison matrices were constructed, and the Eigenvector Method was used to compute the weights. The consistency ratio (CR) was calculated for each matrix, with a threshold of $CR < 0.1$ adopted to ensure logical consistency in the comparisons.

Once the criteria weights were determined, the PROMETHEE II method was employed to rank the machining routes. Indicator values were normalized between 0 and 1, and a linear preference function was applied to each criterion. A total of 100 decision scenarios were simulated, representing different weighting combinations among the criteria to reflect varying market and sustainability priorities. This technical implementation ensures the reproducibility of the AHP-PROMETHEE analysis and allows flexibility to explore different decision-making contexts.

In order to obtain the ideal cutting parameters for the production of the part based on sustainability indicators, the AHP-Promethee methodology was used to rank and select the optimal set of cutting speed, feed rate, depth of cut, and lateral depth. These four parameters are directly related to all sustainability indicators. For simulation purposes, the study was conducted using the parameters provided by the tool manufacturer Sandvik CoroPlus® [28]. The material selected for the simulation is ASTM F67 Gr.2 titanium, and the specified lubrication for the simulation is a 5% concentration soluble oil emulsion. The selection of parameters was based on the acceptable usage ranges of the tool. Table IV presents the selection of cutting parameters, where the simulation ranges generate a combination of possible alternatives for the production of the implant. Table III shows the values created for milling, and Table V shows the parameters for the drilling process.

TABLE III
RANGE OF VALUES FOR SETTING UP THE PRODUCTION SCENARIOS.

Range	Drilling		Milling			
	Vc (m/min)	Fz (mm/rot.)	Vc (m/min)	Fz (mm/dente)	Ap (mm)	Ae (mm)
Min.	15	0.065	26	0.05	1	8
25%	18	0.0725	30	0.875	1.5	10
50%	20.5	0.08	35	0.125	2	12
75%	23	0.0875	40	0.165	2.5	14

Max.	26	0.095	43	0.2	3	16

As can be seen from the data in the previous section, the choice of the best combination or the best route is a decision that must be made from the perspective of several criteria. For this reason, the Analytic Hierarchy Process was chosen to assign weights to each criterion, and the PROMETHEE method was selected for choosing the route. The choice of these methods was based on researches that address similar problem-solving scenarios and because these methods provide good consistency [34], [35].

$$If \text{ the objective is to maximize. then } R_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{12}$$

$$If\ the\ objective\ is\ to\ minimize.then\ R_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{13}$$

Where: x_{ij} = Value of alternative i in criterion j; R_{ij} = Normalized value of alternative i in criterion j; min_{ij} = Lowest value among all alternatives for criterion j; max_{ij} = Highest value among all alternatives for criterion j.

$$\pi(a.b) = \sum_{j=1}^{k} P_j\ (a.b) * w_j \tag{14}$$

$$\pi(b.a) = \sum_{j=1}^{k} P_j\ (b.a) * w_j \tag{15}$$

$$\pi(a.a) = 0 \tag{16}$$

$$0 \leq \pi(a.b) \leq 1 \tag{17}$$

$$0 \leq \pi(b.a) \leq 1 \tag{18}$$

$$0 \leq \pi(a.b) + \pi(b.a) \leq 1 \tag{19}$$

$$Phi^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a.x) \tag{20}$$

$$Phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x.a) \tag{21}$$

$$Phi(a) = Phi^{+}(a) - Phi^{-}(a) \tag{22}$$

Where: л(a,b) = Expresses the degree to which "a" is preferred over "b"; л(b,a) = Expresses the degree to which "b" is preferred over "a"; Pj(a,b) = Preference value of "a" over "b"; Pj(b,a) = Preference value of "b" over "a"; Wj = Weight of criterion jjj in the decision-making process; Phi+ = Positive outranking flow of the alternative; Phi- = Negative outranking flow of the alternative; Phi = Balance between the positive and negative outranking flows.

Analyzing the product demand in the market during the development of this study, three different scenarios were identified, classified as follows: Demand for 48 pieces per day - Regular scenario; Demand for 62 pieces per day - High demand scenario (30% increase); Demand for 24 pieces per day - Crisis, low demand, or pandemic scenario (100% reduction in demand).

The choice of the production route can change according to the demand. The production system must ensure delivery deadlines to the customer while avoiding excessive stock during a crisis scenario (100% reduction in demand). Therefore, selecting a route for controlling the inputs used in production during a crisis, and choosing another route to ensure product delivery in a high-demand scenario, becomes necessary. These changes in the combination of production parameters can provide the company with a market advantage.

RESULTS AND DISCUSSIONS

After applying sustainability indicator equations to all the routes developed, the interaction between the parameters involved in the study can be graphically analyzed. The results indicated that the high demand for medical products for fracture treatment, combined with the increase in global life expectancy, highlights the critical need for adopting technologies that optimize the use of natural resources. Demand emerges as the most influential factor in scenario creation, making it essential to assess production capacity to ensure demand fulfillment.

Table IV presents the input data for the 84 evaluated routes, combining parameters related to clamping, cutting processes, milling, and drilling. ASTM F67 Grade 2 titanium, as a high-grade material, requires a detailed understanding of machining phenomena and parameters, making it essential to align them with sustainability through multicriteria decision-making methods. Routes 79 to 84 represent the parameters initially proposed by the cutting tool manufacturer.

The application of an MCDM system in corporate environments enables the selection of the most efficient and sustainable production route, adjusting parameters to different scenarios. As a result, decisions optimize productivity, organize the workforce, and minimize waste, establishing a robust link between processes and supply chains.

TABLE IV
PRODUCTION ROUTES FOR THE MANUFACTURING PROCESS.

Scenario	Cutting machine	Fixture (pieces)	Vc(m/min)	Ap(mm)	Ae(mm)	Fz(mm)	Vc(m/min)	Fz(mm)
			Milling				Drilling	
1	Water jet	1	28	1	8	0.05	15	0.065
2	Water jet	3	28	1	8	0.05	15	0.065
3	Water jet	5	28	1	8	0.05	15	0.065
4	Water jet	1	27	1	16	0.05	15	0.065
5	Water jet	3	27	1	16	0.05	15	0.065
6	Water jet	5	27	1	16	0.05	15	0.065
7	Water jet	1	26	1	16	0.1	15	0.07
8	Water jet	3	26	1	16	0.1	15	0.07
9	Water jet	5	26	1	16	0.1	15	0.07
10	Water jet	1	35	2	16	0.15	18	0.085
11	Water jet	3	35	2	16	0.15	18	0.085
12	Water jet	5	35	2	16	0.15	18	0.085
13	Water jet	1	35	2	16	0.2	22	0.085
14	Water jet	3	35	2	16	0.2	22	0.085
15	Water jet	5	35	2	16	0.2	22	0.08
16	Water jet	1	35	3	16	0.2	26	0.09
17	Water jet	3	35	3	16	0.2	26	0.09
18	Water jet	5	35	3	16	0.2	26	0.09
19	Water jet	1	43	3	16	0.2	26	0.095
20	Water jet	3	43	3	16	0.2	26	0.095
21	Water jet	5	43	3	16	0.2	26	0.095
22	Water jet	1	30	3	16	0.2	22	0.095
23	Water jet	3	30	3	16	0.2	22	0.095
24	Water jet	5	30	3	16	0.2	22	0.095
25	Water jet	1	25	3	16	0.2	15	0.095
26	Water jet	3	25	3	16	0.2	15	0.095
27	Water jet	5	25	3	16	0.2	15	0.095
28	Water jet	1	35	3	16	0.2	15	0.07
29	Water jet	3	35	3	16	0.2	15	0.07
30	Water jet	5	35	3	16	0.2	15	0.07
31	Water jet	1	27	3	16	0.2	15	0.085
32	Water jet	3	27	3	16	0.2	15	0.07
33	Water jet	5	27	3	16	0.2	15	0.07
34	Water jet	1	30	3	16	0.2	15	0.065
35	Water jet	3	30	3	16	0.2	15	0.065
36	Water jet	5	30	3	16	0.2	15	0.065
37	Water jet	1	27	3	16	0.2	15	0.065
38	Water jet	3	25	3	16	0.2	15	0.065
39	Water jet	5	25	3	16	0.2	15	0.065
40	WEDM	1	28	1	8	0.05	15	0.065

41	WEDM	3	28	1	8	0.05	15	0.065
42	WEDM	5	28	1	8	0.05	15	0.065
43	WEDM	1	27	1	16	0.05	15	0.065
44	WEDM	3	27	1	16	0.05	15	0.065
45	WEDM	5	27	1	16	0.05	15	0.065
46	WEDM	1	26	1	16	0.1	15	0.07
47	WEDM	3	26	1	16	0.1	15	0.07
48	WEDM	5	26	1	16	0.1	15	0.07
49	WEDM	1	35	2	16	0.15	18	0.085
50	WEDM	3	35	2	16	0.15	18	0.085
51	WEDM	5	35	2	16	0.15	18	0.085
52	WEDM	1	35	2	16	0.2	22	0.085
53	WEDM	3	35	2	16	0.2	22	0.085
54	WEDM	5	35	2	16	0.2	22	0.08
55	WEDM	1	35	3	16	0.2	26	0.09
56	WEDM	3	35	3	16	0.2	26	0.09
57	WEDM	5	35	3	16	0.2	26	0.09
58	WEDM	1	43	3	16	0.2	26	0.095
59	WEDM	3	43	3	16	0.2	26	0.095
60	WEDM	5	43	3	16	0.2	26	0.095
61	WEDM	1	30	3	16	0.2	22	0.095
62	WEDM	3	30	3	16	0.2	22	0.095
63	WEDM	5	30	3	16	0.2	22	0.095
64	WEDM	1	25	3	16	0.2	15	0.095
65	WEDM	3	25	3	16	0.2	15	0.095
66	WEDM	5	25	3	16	0.2	15	0.095
67	WEDM	1	35	3	16	0.2	15	0.095
68	WEDM	3	35	3	16	0.2	15	0.095
69	WEDM	5	35	3	16	0.2	15	0.095
70	WEDM	1	43	3	16	0.2	15	0.095
71	WEDM	3	43	3	16	0.2	15	0.095
72	WEDM	5	43	3	16	0.2	15	0.095
73	WEDM	1	30	3	16	0.2	26	0.095
74	WEDM	3	30	3	16	0.2	26	0.095
75	WEDM	5	30	3	16	0.2	26	0.095
76	WEDM	1	25	3	16	0.2	26	0.095
77	WEDM	3	25	3	16	0.2	26	0.095
78	WEDM	5	25	3	16	0.2	26	0.095
79	Water jet	1	36.3	3	13.5	0.135	20.5	0.08
80	Water jet	3	36.3	3	13.5	0.135	20.5	0.08
81	Water jet	5	36.3	3	13.5	0.135	20.5	0.08
82	WEDM	1	36.3	3	13.5	0.135	20.5	0.08
83	WEDM	3	36.3	3	13.5	0.135	20.5	0.08
84	WEDM	5	36.3	3	13.5	0.135	20.5	0.08

As shown in Table V, the study's outcome resulted in the selection of two alternatives, referred to as “A” and “B.” The chosen processes involve clamping one part per cycle, with the most appropriate route defined for each production scenario using the Analytical Hierarchy Process and the PROMETHEE method. Routes requiring higher initial investment and greater labor input ranked lower in the evaluation.

TABLE V
PRODUCTION PARAMETERS FOR THE SELECTED ROUTES.

	Rota 37	Rota 64
Cutting process	Water jet	WEDM
Fixture	1 piece	1 pieces

Cutting speed in milling (m/min)	27	25
Depth of cut in milling (Ap) mm	3	3
Stepover in milling (Ae) mm	16	16
Feed per tooth in milling (mm/z)	0.2	0.2
Life of the tool in milling (min.)	55	60
Time of the milling (min)	3.39	0.79
Cost per piece with the tool in the milling (R$)	4.94	1.05
Time to change the tool in milling (min)	0.93	0.20
Total time in milling (min)	4.32	0.98
Weight in Kg of the carbide used per piece in milling	0.01	0.01
Cutting speed in drilling (m/min)	15	15
Feed per tooth in drilling (mm/z)	0.065	0.095
Life of the tool in drilling (min.)	85	53
Feed in drilling (mm/z)	69.3	101.3
Length in drilling	70	70
Time of the drilling (min)	1.2	0.9
Cost per piece with the tool in the drilling (R$)	3.5	4.2
Time to change the tool in drilling (min)	0.2	0.3
Total time in drilling (min)	1.4	1.1
Weight in Kg of the carbide used per piece in drilling	0.0	0.0
Length of the path to cut the raw material	144	133
Cutting speed (mm/min) in the cutting process	15	3.7
Machining time (min)	8.7	5.1
Time of the water jet / WEDM (min)	12.6	36.0
Total cost (R$)	100.5	102.8
Daily production capacity	50	85
Initial investment (R$)	25272.5	25778.7
Training time (hours)	4	6
Worker safety	1	1
Labor time per piece	4.1	3.4
Energy consumption (Kw/h)	5.3	10.3
Volume of the titanium used per piece	17.5	1.8
Waste in carbide per piece (g)	1.0	0.6

In the graphs presented in Figure 2 (with the red point indicating route “A” and the yellow point representing route “B”), the cutting speeds are in the lower ranges, as illustrated in Figures 2-a (milling) and 2-d (drilling). This choice aims to extend tool life, thereby reducing downtimes and labor costs. Under normal demand conditions, simple devices and water cutting are preferred, with speeds and depths set within recommended limits to ensure optimal performance.

In an economic downturn, production halts after meeting the minimum demand to prevent excessive inventory, conserving inputs and energy. Figure 2-e shows that greater investment in clamping devices and tools does not proportionally increase production. Figure 2-f compares energy consumption per part, with the data on the left corresponding to water cutting and those on the right to wire electrical discharge machining (WEDM).

In high-demand scenarios, the WEDM route stands out, increasing capacity to 85 parts when the demand is 62. In these cases, simple clamping devices and more aggressive cutting parameters are preferable, enabling faster tool changes.

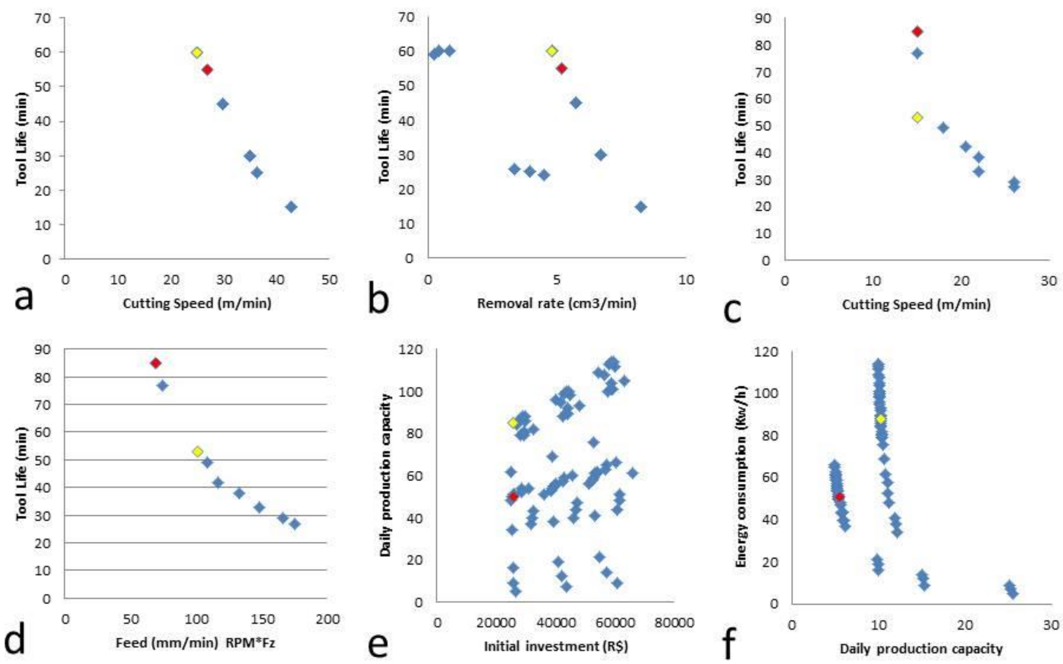


FIGURE 2
GRAPHICAL ANALYSIS OF PARAMETERS SELECTED BY THE MCDM SYSTEM (SOURCE: AUTHORS OWN WORK).

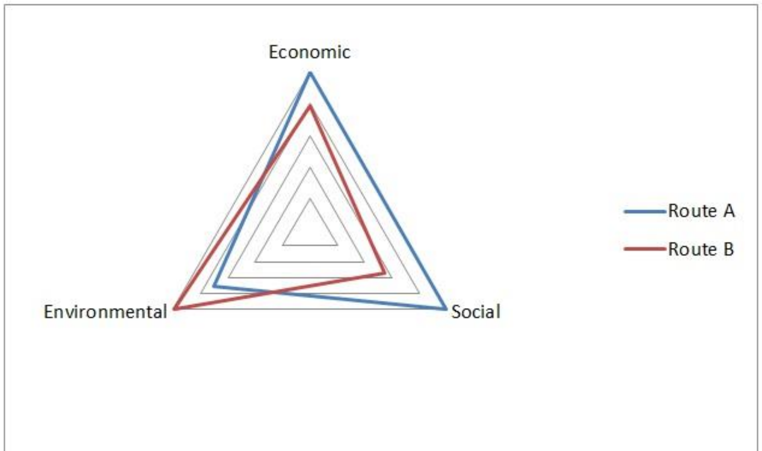
Regarding the routes defined by the MCDM system, similarities were observed in terms of costs, initial investment, and worker safety. Route "B" achieved 70% higher production capacity, while route "A" required 33% less training time due to the simplicity of water cutting, which does not necessitate dimensional control of the final profile.

Beyond presenting absolute values for energy consumption, titanium usage, and carbide waste in Table V, these metrics were further analyzed to assess their environmental implications. Specifically, CO_2 equivalent emissions were estimated based on the calculated energy consumption for each route, applying the carbon intensity factor of 0.084 kg CO_2 per kWh. This provided a clearer comparison of the environmental footprint associated with each machining process, with wire EDM routes exhibiting proportionally higher emissions due to greater energy use.

Although titanium consumption and carbide waste were not directly converted into CO_2 equivalents, these factors remain critical environmental indicators. Titanium usage reflects the depletion of raw material resources, while carbide waste represents the environmental burden of tool wear and disposal. Their integration into the multicriteria decision analysis ensured a holistic sustainability evaluation, balancing economic, social, and environmental considerations. The normalization of these metrics allowed them to be weighted equally in the comparative assessment, supporting robust decision-making across production scenarios.

Economic indicators provided clear insights into productivity and costs, while social indicators helped organize the workforce. Environmental indicators focused on minimizing waste and raw material consumption, offering a solid foundation for multicriteria decision-making.

The operating time was longer in route “A,” requiring more supervision and tool changes. Conversely, route “B” consumed more energy due to the WEDM process but demonstrated higher efficiency in titanium utilization. Thus, the selected routes proved suitable for each production scenario, adjusting capacity and costs as needed. Figure 3 presents the normalized data of the sustainability indicators obtained for the routes selected through the AHP-PROMETHEE process.



	Economic	Social	Environmental
Route A	1,0000	1,0000	0,7063
Route B	0,7893	0,5432	0,9956

FIGURE 3
NORMALIZED SUSTAINABILITY FACTOR FOR THE ROUTES SELECTED BY THE MCDM SYSTEM (SOURCE: AUTHORS OWN WORK).

According to Figure 3, Route 37, which has the highest selection percentage, covers all three pillars of sustainability, with the best results in the economic and social domains. This is due to the combination of process parameters, the choice of the fixation device, and the production workflow, which together result in low initial investment, costs, and suitable production times, while maintaining a production capacity that meets normal market demand. This production route was adopted by the company where the research was conducted because of its advantages over the other options.

Route 64, on the other hand, has a distinct scope. This production route is suitable for situations requiring high-demand fulfillment and notably focuses on environmental indicators. Its strong performance in this area is due to the cutting process, which saves raw materials and hard metals used in production. However, this route does not perform well economically; the cutting time is longer, and the initial investment and costs are less favorable compared to Route 37. In the social domain, Route 64 scores lower because the operational training time required for wire EDM operation is higher. For the remaining social indicators, this route has values similar to those of Route 37.

The manufacturing routes and parameters evaluated in this study were defined based on real operational data from a Brazilian medical implant manufacturer, ensuring alignment with practical production constraints and market conditions. Although specific operational details remain confidential, the scenarios analyzed mirror actual demand variability and machining requirements in the biomedical sector.

Furthermore, similar academic-industry collaborations in biomedical manufacturing have successfully demonstrated the practical relevance of decision-support frameworks, such as cost estimation models for additive manufacturing (AM) of custom implants [36] and hybrid manufacturing strategies combining AM and subtractive methods for titanium implants [37]. These studies reinforce the industrial applicability of multicriteria approaches like the one proposed here, which integrates economic, environmental, and social dimensions to support sustainable decision-making. Future research will aim to expand these collaborations and include comparative validations with state-of-the-art manufacturing technologies, as highlighted in related case studies [38], [39].

CONCLUSION

This study demonstrated that adopting sustainable production routes is essential to meet the growing demand for medical products while optimizing resource usage. The comparative analysis between routes “A” and “B” revealed that, although route “A” required 33% less training time due to the simplicity of water cutting, its production capacity was 70% lower compared to route “B,” which employed wire electrical discharge machining. On the other hand, route “B” exhibited higher energy consumption but was more efficient in titanium utilization, achieving a production of up to 85 pieces when the demand was 62.

The findings of this study offer direct implications for both manufacturers and policymakers. For manufacturers, the proposed methodology supports the selection of optimal machining routes aligned with specific operational goals, whether prioritizing cost reduction, energy efficiency, or material utilization, depending on demand conditions. For instance, under scenarios of regular or low demand, water jet cutting combined with optimized milling parameters emerges as the most sustainable route, whereas wire EDM becomes preferable in high-demand contexts requiring increased productivity.

From a policymaking perspective, the integration of environmental impact metrics, such as CO_2 equivalent emissions, into the decision framework allows for informed regulatory or fiscal incentives. Policymakers aiming to promote sustainable manufacturing practices could leverage such frameworks to encourage the adoption of machining strategies that minimize environmental impacts without compromising economic viability. The flexibility of the AHP-PROMETHEE approach facilitates its adaptation to different policy priorities, enabling decision-makers to adjust criteria weights in alignment with evolving regulatory or market conditions. This adaptability makes the proposed methodology a valuable tool for both strategic industrial planning and policy formulation aimed at fostering sustainable manufacturing ecosystems.

In economic downturn scenarios, halting production after meeting minimal demand prevented excess inventory and saved inputs and energy. In high-demand scenarios, using more aggressive cutting parameters and simple clamping devices allowed higher productivity and faster tool changes.

The use of economic, social, and environmental indicators enabled a comprehensive analysis: economic indicators optimized productivity and costs, social indicators organized the workforce efficiently, and environmental indicators minimized waste and raw material consumption. Thus, the selected production routes proved effective in adjusting capacity and costs as needed, ensuring operational efficiency and sustainability across different scenarios.

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