Comparative Analysis of Additive Manufacturing and CNC Machining in Dental Implant Production: Energy Consumption and Material Efficiency

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***Abstract* – The development of digital technologies in dentistry has enabled the implementation of new manufacturing processes for the production of dental implants. Additive manufacturing represents an alternative to conventional CNC machining, offering increased design flexibility and more efficient material utilization. The aim of this paper is to analyze and compare additive manufacturing and CNC machining in the production of dental implants in terms of energy consumption, material efficiency, and environmental impact. The study examines the most commonly used technologies, including Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Stereolithography (SLA), and multi-axis CNC machining. The analysis focuses on the specific energy consumption of the processes and the influence of manufacturing factors such as implant geometric complexity, production volume, and the need for post-processing operations. The analysis showed that additive manufacturing enables the production of complex porous structures while significantly reducing material waste, although at the cost of higher specific energy consumption. In contrast, CNC machining achieves higher dimensional accuracy and lower direct energy consumption per part, albeit with substantially greater material loss.**

Environmental and energy performance are primarily influenced by production volume, implant geometry, and post-processing requirements. These variables highlight the potential benefits of employing a hybrid manufacturing approach that combines additive manufacturing and CNC machining.

***Keywords* – additive manufacturing, CNC machining, dental implants, energy efficiency, environmental aspects.**

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1. Introduction

The manufacturing process of dental implants is significantly influenced by the implementation of additive manufacturing technologies, commonly referred to as 3D printing. The use of intraoral scanning in conjunction with CAD/CAM systems enables the design of implants that accurately replicate the patient's individual anatomy. This digital approach ensures a high degree of geometric conformity between the final product and biological structures. The implementation of this workflow allows the direct conversion of clinical data into the final implant form, thereby eliminating redundant intermediate steps typical of conventional manufacturing. In contrast to traditional subtractive methods, such as CNC machining based on material removal from a semi-finished workpiece, additive manufacturing (AM) processes create products through the successive deposition of material layers. This approach enables the fabrication of highly complex geometries, particularly defined porous structures that enhance osseointegration, as well as functionally graded materials (FGMs). The production of such features using conventional machining is often technically challenging and economically inefficient.

In contemporary dentistry, additive manufacturing is applied in the production of crowns, bridges, surgical guides, and dental implants themselves [1]. Key factors for achieving primary stability and successful recovery include processing accuracy and surface quality.

Furthermore, personalized implants reduce the need for intraoperative adjustments, leading to improved clinical outcomes. A significant advantage of additive technologies is their high material efficiency. In CNC machining, a substantial portion of the titanium stock is converted into waste in the form of chips, whereas powder-based AM technologies fuse only the material required for the final geometry. The remaining powder can be reused within the process. Available studies indicate that while subtractive processes utilize approximately 20-40% of the input material, additive methods achieve yields exceeding 80% [2].

Despite these advantages, additive manufacturing faces certain limitations. Selected technologies may exhibit higher surface roughness or dimensional deviations, necessitating subsequent post-processing. Although the mechanical properties of AM implants have been extensively studied, issues related to their long-term biocompatibility and microbiological stability require more systematic evaluation. For broader clinical adoption, the implementation of standardized protocols is therefore essential. Current research also increasingly focuses on the energy and environmental aspects of manufacturing. Due to minimal material waste, additive manufacturing appears to be a more sustainable alternative. However, it has to be considered that powder bed processes exhibit higher specific energy consumption, primarily due to the operation of laser systems [3]. CNC machining, while demonstrating lower direct energy consumption per part, generates significant amounts of waste, the recycling of which is energy intensive.

In light of the above, a comprehensive assessment of implant manufacturing sustainability requires the simultaneous evaluation of energy demand and material efficiency. This forms the basis for comparing additive technologies and CNC machining in terms of energy consumption, resource utilization, and environmental impact. Within this analysis, particular attention is therefore given to the influence of production volume and implant geometric complexity on the observed parameters.

2. Current State of Dental Implant Manufacturing

At present, the manufacturing of dental implants is carried out through a combination of conventional subtractive machining technologies and modern additive manufacturing processes, which are integrated into a digital workflow based on CAD/CAM systems. Standardized screw-type implants and a significant proportion of abutments are primarily produced using CNC machining, with the geometry of the final component derived from three-dimensional data obtained through CBCT imaging and intraoral scanning.

The digital implant design is subsequently transformed within a CAD environment into NC code, which serves to control the sequence of technological operations, including turning, multi-axis milling, drilling, and final surface finishing processes. Upon completion of machining, metrological verification of dimensional accuracy is performed, followed by sterilization of the final product prior to clinical application [4].

In parallel with conventional manufacturing approaches, an increasing trend in industrial practice is the implementation of additive manufacturing technologies, which enable the production of individually shaped components through the layer-by-layer deposition of material based on a digital CAD model. In dental implantology, 3D printing is primarily applied in the production of surgical guides, implantological models, custom trays, and other auxiliary tools used in the planning and execution of implant procedures. Powder-based additive processes, particularly Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM), are also employed in the fabrication of personalized titanium meshes for augmentation procedures, implant-supported framework structures, and, in specific cases, individualized implants with defined porous architectures that promote osseointegration [5], [6].

Despite the extensive body of literature addressing additive manufacturing and CNC machining in dental implantology, research has predominantly focused on material mechanical properties, dimensional accuracy, and clinical performance of implants. Energy efficiency and environmental aspects of manufacturing processes have received comparatively less attention, and systematic comparisons between the two manufacturing approaches remain limited. Furthermore, only a limited number of studies comprehensively evaluate energy consumption, material waste generation, and environmental impacts under real-world dental implant production conditions.

2.1. Additive Manufacturing Technologies in Dental Implantology

In the field of dental implantology, additive manufacturing has been progressively established as a relevant technological alternative to conventional subtractive manufacturing processes. Within implantological applications, three main groups of additive technologies can be identified, differing in their material processing principles and the nature of the input medium. These include technologies based on vat photopolymerization (VPP), powder bed fusion (PBF), and material extrusion (MEX) [1].

Vat photopolymerization technologies are based on the selective curing of liquid photopolymer resins using a light source. In stereolithography (SLA), a UV laser is employed to polymerize thin resin layers with a high degree of precision, enabling the production of detailed surgical guides and accurate anatomical models. In digital light processing (DLP), a projection system is used to expose an entire material layer simultaneously, resulting in reduced manufacturing time, albeit with slightly lower resolution compared to stereolithography [5].

The Continuous Liquid Interface Production (CLIP) technology enables continuous object formation without discrete layer separation, achieving improved surface quality due to a controlled polymerization zone [3]. PolyJet technology is based on the deposition of microdroplets of photopolymer material, which are subsequently cured by UV radiation, resulting in high dimensional accuracy of the final product [5].

In powder bed-based technologies such as Selective Laser Melting (SLM) and Selective Laser Sintering (SLS), a high-power laser is used as an energy source to selectively sinter or melt metallic and polymer powders layer by layer. In Electron Beam Melting (EBM), an electron beam is used instead of a laser, and the entire process is conducted in a vacuum environment.

This technology is considered particularly suitable for processing titanium alloys widely used in dental implantology [4]. These technologies enable the fabrication of porous and topologically optimized structures that support the process of osseointegration.

Material extrusion technologies (MEX), primarily represented by Fused Deposition Modeling (FDM), are based on the extrusion of molten thermoplastic filament through a heated nozzle, with material deposited layer by layer according to a digital model [3]. Although this technology achieves lower resolution compared to VPP or PBF processes, it is considered a cost-effective solution and is often applied in the production of anatomical models, surgical guides, or temporary components.

In practical applications, individual manufacturing technologies are often combined. Metal implants produced using PBF processes are subsequently finished by CNC machining to achieve the required dimensional accuracy and surface quality [5]. Manufacturing technology is selected according to material properties, accuracy requirements, product geometry, and clinical application.

Table 1. Classification of additive manufacturing technologies, their applications in dentistry, and accuracy

Technology	Group	Material	Typical applications	Accuracy / Tolerance
SLA	VPP	Photopolymer	Surgical guides, models	**±0.05–0.15 mm**
DLP	VPP	Photopolymer	Models, crowns	**±0.05–0.15 mm**
SLM / DMLS	PBF	Titanium, Co-Cr	Implants	**±0.05–0.10 mm**
EBM	PBF	Titanium	Implants	**±0.10–0.20 mm**
FDM / MEX	MEX	PLA, ABS	Models	**±0.1–0.3 mm**
CNC machining	Subtractive	Titanium (block)	Implants	**±0.005 mm**

As shown in Table 1, CNC machining achieves higher dimensional accuracy and tighter tolerance ranges than most additive manufacturing technologies. This is a significant factor in the production of final metallic components such as dental implants. CNC machining enables the processing of a wide range of materials while maintaining minimal tolerance deviations. In contrast, additive technologies, including SLA, DLP, SLM/DMLS, and FDM, are characterized by reduced material waste and increased design flexibility, although their accuracy and energy demands vary depending on the specific technology employed. In additive manufacturing, material is deposited exclusively in locations defined by the digital model, whereas in CNC machining, material is removed from a semi-finished workpiece in the form of chips.

The selection of appropriate manufacturing technology is therefore primarily determined by the material used, the required level of accuracy, and the overall efficiency of the production process.

Additive manufacturing represents a suitable alternative for the production of personalized components. Material is deposited only where required by the final geometry, resulting in a significant reduction in material waste compared to conventional subtractive processes [7]. This approach is particularly advantageous for small-batch production and for implants with high geometric complexity.

Economically, AM is attractive for individualized production because it eliminates dedicated tooling requirements. In contrast, for large-scale production of standardized implants, CNC machining remains a more cost-effective solution and is associated with lower energy consumption per part [8].

Among the limitations of additive manufacturing is the requirement for post-processing operations, including the removal of support structures, heat treatment, and subsequent surface finishing. Certain technologies may exhibit increased surface roughness or dimensional deviations, necessitating additional machining to achieve the desired surface quality and dimensional accuracy. In addition to technological considerations, it is also necessary to address issues related to the biocompatibility of photopolymeric materials and the need for further clinical validation of their long-term stability and safety in medical applications [4].

2.2. CNC Technologies in Dental Manufacturing

CNC machining is a key manufacturing technology in dental implantology, utilized for the precise production of metallic components based on digital CAD/CAM data. Digital three-dimensional models obtained from intraoral scans or from scanning physical models are processed in CAD software and subsequently converted within CAM systems into tool paths that control the manufacturing process on CNC machines. The production itself is carried out using a subtractive approach, in which material is progressively removed from blocks of biocompatible materials, most commonly titanium. CNC machines achieve micrometer-level dimensional accuracy and high repeatability, which are essential prerequisites for the precise fitting of implant components and framework structures. Modern CNC technologies enable the machining of a wide range of materials, including metals, ceramics, and polymers. These technologies constitute an integral part of digital workflows in dental manufacturing, ensuring high quality and reproducibility of production processes [10].

CNC machining is applied in the final production of titanium implant components, including implant parts, abutments, connecting elements, and precision framework structures for implant-supported prostheses, where high dimensional accuracy and superior surface quality of functional surfaces are required (see Figure 1).

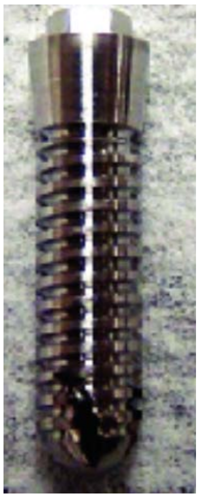

Figure 1. Dental implant manufactured on a CNC machining center [11]

CNC machining is also frequently used for the final finishing of dental implants manufactured using AM technology [9].

2.3. Comparison of AM and CNC Machining

Additive manufacturing and CNC machining represent two complementary approaches within digital manufacturing, differing in both the principle of process realization and their technological characteristics. In additive manufacturing, a product is created through the successive layering of material directly based on a digital CAD model, with the consumed material volume only slightly exceeding that of the final part. As a result, material waste is minimized. This approach enables the fabrication of geometrically complex structures, including lattice architecture, internal channels, porous surfaces, and topologically optimized shapes. The production of such features using conventional CNC machining is technically demanding or, in some cases, not feasible. Among the limitations of additive manufacturing are higher energy consumption, primarily due to the operation of laser systems and the heating of the building chamber, as well as higher capital investment costs and longer production times per part in large-scale manufacturing [12].

In the production of dental implants using additive technologies, laser-based systems for processing metallic materials (SLM/DMLS) and optical systems for polymer processing (SLA, DLP) are employed. CNC machining of titanium and other biocompatible materials represents a well-established technological approach for manufacturing precise implant components. Energy consumption plays an important role in both environmental and economic sustainability. CNC machines provide high repeatability of dimensional accuracy and a high level of automation, enabling the machining of complex geometries and fine details that complement or finalize components produced by additive technologies [13].

In additive manufacturing of dental implants, different material processing principles are applied depending on the physical and technological properties of the materials. For metallic components, laser-based systems such as Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) are used, achieving high spatial accuracy in producing geometrically complex structures. For polymer components and auxiliary parts, optical systems such as stereolithography (SLA) and digital light processing (DLP), as well as Fused Deposition Modeling (FDM), are utilized, particularly in the production of models and surgical guides (see Figure 2).

The energy demand of these manufacturing processes represents a critical factor for both environmental and economic sustainability, as it includes not only the energy consumption of the primary functional units of the equipment but also that of auxiliary systems required to ensure stable operation of the technological process during the production of components from various material types [9].

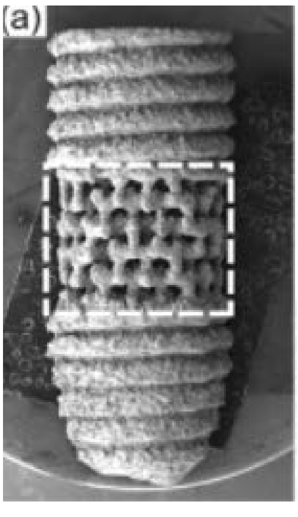

Figure 2. A dental implant manufactured using 3D printing [9]

Research studies indicate that the Specific Energy Consumption (SEC) associated with metal powder bed fusion (PBF) processes, including Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS), reach relatively high values. The exact SEC value depends on the type of equipment and the configuration of process parameters, such as build chamber size, layer thickness, and the duration of the active processing phase. Within energy planning, SEC is considered a key performance indicator. Reported values range from tens to hundreds of megajoules per manufactured part, depending on the efficiency of machine utilization. These values exceed the energy demands of conventional machining processes; however, additive manufacturing significantly reduces material waste, particularly in the production of geometrically complex components.

After the completion of the printing process, the metal part is mechanically separated from the build platform using electrical discharge machining (EDM). Subsequently, support structures are removed, followed by cleaning and final surface finishing. These post-processing operations introduce additional energy consumption, which has to be included in a comprehensive evaluation of the overall energy demand of the manufacturing process [14].

In stereolithography (SLA) and digital light processing (DLP), energy consumption is generated not only by the laser or projection unit but also by auxiliary subsystems required for machine operation. Energy is consumed by motion systems, resin tank heating systems, and cooling units. Optimization of process parameters, such as part orientation and layer thickness, represents an effective approach to reducing the overall energy burden of the manufacturing process.

For polymer-based additive technologies, it is reported that the specific energy consumption in stereolithography (SLA) reaches levels comparable to metal AM processes, typically in the range of tens to hundreds of MJ/kg. In the case of Fused Deposition Modeling (FDM), energy consumption depends on the material used, part geometry and process parameter settings. For polymer materials, post-processing operations such as cleaning and additional curing also contribute to the total energy demand, increasing overall energy consumption by several tens of percent compared to the printing process alone [12].

2.4. Energy Consumption of CNC Machining

CNC machining represents the predominant technological approach in the manufacturing of titanium dental implants. It is a subtractive process in which the implant is produced by material removal from a titanium workpiece in the form of chips. The primary energy consumer during the machining process is the spindle motor, with a nominal power of 5-20 kW. During the active machining phase, approximately 40–70% of its capacity is utilized, corresponding to a power range of 4-7 kW. For a production cycle lasting 30 minutes, the energy consumption associated with machining reaches approximately 3.5-5.5 kWh per implant, including the energy consumption of axis drives and auxiliary motors.

A significant component of the overall energy balance is represented by cooling systems. Cooling pumps with a power rating of 2-5 kW, together with external cooling units, constitute a major factor in the energy demand of the process. The energy consumption for cooling ranges from 2.5 to 5.5 kWh per implant, depending on the operating mode of the equipment and its utilization intensity.

CNC machines also consume energy outside the active machining phase. In standby mode, the equipment exhibits a power consumption of approximately 2-4 kW.

Tool wear is another factor influencing the energy demand of the process. As cutting conditions deteriorate, energy consumption for machining increases by approximately 10-20%, while additional surface finishing is required to achieve the desired quality of functional surfaces.

CNC machining is characterized by a high proportion of material waste. An implant with a mass of 2-4 g is typically produced from a titanium workpiece weighing 15-30 g, meaning that approximately 80-90% of the input material is removed in the form of chips. The recycling of titanium chips represents an additional energy burden, which must be taken into account when evaluating the overall environmental impact of the manufacturing process [15].

3. Comparison of Energy Efficiency and Material Consumption in CNC Machining and Additive Manufacturing Technologies

Additive manufacturing and CNC machining differ not only in the principle of part formation but also in the structure of energy consumption. In additive processes, such as SLM/DMLS and SLA/DLP, a significant portion of the total energy consumption is attributed to the radiation source (laser or projection system).

A substantial share of energy is also consumed by auxiliary subsystems ensuring stable machine operation, including heating units, ventilation systems, and cooling circuits. The overall energy balance has to also account for post-processing operations, such as electrical discharge machining (EDM) for part separation, removal of support structures, and cleaning. These operations further increase the total energy demand associated with the production of metal implants [16].

In CNC machining, energy consumption is primarily concentrated in the active cutting phase, during which the main sources of energy demand are the spindle motor and axis drives. Cooling systems and standby energy consumption also represent significant components of the total energy balance. The energy consumption of the machining process itself is relatively stable and predictable. However, the overall environmental balance is affected by the high proportion of material waste, as a substantial part of the workpiece is removed in the form of chips.

Additive manufacturing generally requires more energy because both printing and post-processing contribute substantially to total consumption. In contrast, CNC machining achieves lower direct energy consumption per manufactured part but exhibits lower material efficiency. The resulting energy efficiency of both manufacturing approaches is influenced by several factors, including the geometric complexity of the part, production batch size, and the degree of optimization of technological parameters within the manufacturing process [17].

Table 2. Comparison of the energy components involved in the production of metal implants using SLM/DMLS technology and CNC machining

Phase / energy component	AM technology	CNC machining
Main energy source	Laser (~40 %)	Spindle motor (4–7 kW)
Support subsystems	~60 % (pumps, heating, inert gas, cooling)	Axis drives + auxiliary motors (1–2.5 kWh)
Energy from active generation	7–14 kWh/part (depends on the layer and volume)	3.5–5.5 kWh/part
Cooling	Part of support systems	2.5–5.5 kWh/part
Post-processing	7–8 kWh (EDM) + 2–3 kWh for cleaning	Minimal (grinding, finishing)
Standby mode	A relatively low proportion	1.5–2.5 kWh/part
Specific energy consumption (SEC)	85–508 $MJ \cdot kg^{-1}$	Significantly lower (approx. 0.8–10 $MJ \cdot kg^{-1}$ ekv.)
Material waste	< 5–20 %	80–90 %

Table 2 shows that SLM/DMLS technologies require more energy per manufactured part, mainly because of auxiliary systems and post-processing operations. In contrast, CNC machining achieves lower direct energy consumption during the cutting process itself. However, this manufacturing approach is associated with significant material waste and additional energy requirements related to the operation of cooling systems and the overall functioning of the equipment.

Figure 3 illustrates the differences in energy consumption and material waste between additive manufacturing and CNC machining. An opposite trend is observed in terms of material waste. Additive manufacturing is characterized by a low level of waste due to the selective deposition of material according to the digital model, whereas CNC machining generates a high proportion of waste in the form of chips.

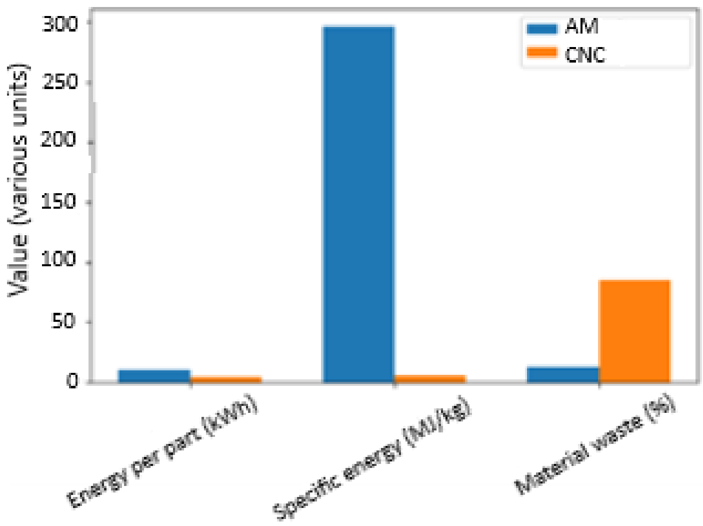

Figure 3. Graphical representation of energy efficiency and material consumption in CNC machining and additive manufacturing technologies

3.1. Factors Affecting Energy Consumption

Energy consumption in the manufacturing of dental implants is influenced by several factors, including product geometric complexity, production volume, and the operational efficiency of the employed technological equipment. In CNC machining, energy demand is closely linked to machining time. For geometrically simpler components, the production cycle is shorter, whereas more complex structures such as internal channels or porous features lead to extended machining times. As geometric complexity increases, the number of tool changes also rises, resulting in higher overall energy consumption. In the case of highly complex geometries, manufacturing becomes technically demanding and less energy efficient.

In additive manufacturing, particularly in SLM/DMLS technologies, a significant portion of energy is consumed to maintain the thermal conditions of the build environment and to perform laser scanning of the powder material. These processes occur largely independently of the geometric complexity of the produced part. In this case, energy consumption is primarily influenced by the volume of material being processed rather than by geometric complexity. This characteristic represents an advantage in the production of personalized or topologically optimized implants.

The energy balance of the manufacturing process is also affected by the number of produced units. In CNC machining, fixed energy costs such as those associated with control systems, cooling units, and standby operation are distributed across individual parts.

As production volume increases, energy consumption per unit decreases, making CNC machining an energy-efficient solution for mass production. In additive manufacturing, the highest energy efficiency is achieved in small- to medium-scale production, where the energy required to heat the building chamber is distributed among multiple parts produced within a single build cycle [18]. The operational efficiency of technological equipment has a significant impact on the overall energy balance. CNC processes are affected by non-productive time associated with machine downtime, tool changes, and parameter setup, which increases overall energy demand. Additive manufacturing systems are typically designed for continuous operation, thereby minimizing non-productive energy consumption. The overall energy efficiency of each manufacturing approach is therefore determined by a combination of product geometric complexity, production volume, and the level of process optimization.

4. Discussion

Decision-making process between additive manufacturing (AM; SLM/DMLS) and CNC machining in the production of dental implants is not based on a single evaluation criterion. In practice, this process is formulated as an optimization problem in which multiple factors are considered simultaneously, including product geometric complexity, production batch size, required dimensional accuracy, and the availability of technological equipment.

In industrial applications, both manufacturing methods are employed in a complementary manner. The basic shape and internal structure of the component are typically produced using additive manufacturing, while critical mating or functional surfaces are subsequently finished locally using CNC machining [19].

4.1. Differences between AM and CNC in Terms of Material Savings, the Production of Complex Geometries and Environmental Considerations

One of the significant advantages of additive manufacturing is its ability to produce complex internal structures without increased material waste. In modern dental implants, porous structures, microchannels, and asymmetric geometries are often designed. In CNC machining, a limiting factor is the physical accessibility of the cutting tool, as well as the increased risk of tool breakage when machining cavities or narrow channels. The production of such features requires conservative cutting conditions, which leads to extended machining time and increased energy consumption.

An additional limitation of CNC machining is the irreversibility of manufacturing errors. In the event of tool failure during the formation of internal features, the component may become irreparable, requiring repetition of the entire production cycle and thereby increasing both energy and material losses, as well as the environmental burden of the process.

In additive manufacturing, porous structures are created directly during the printing process. An implant with a porosity of 30-50%, produced using SLM technology with a material efficiency of 95%, demonstrates significantly lower input material consumption compared to CNC machining, where material efficiency is approximately 30%. In an illustrative example, an implant with a final mass of 1 g and a porosity of 40% contains 0.6 g of material. With additive manufacturing at 95% efficiency, only 0.63 g of titanium powder is required, whereas CNC machining requires a titanium workpiece weighing 2 g. The difference of 1.37 g of titanium does not need to be mined, processed, or transported, thereby reducing the emissions and environmental impact associated with the manufacturing process [20].

From an environmental perspective, the higher material efficiency of additive manufacturing is associated with reduced consumption of primary raw materials, lower volumes of material waste, and a reduction in emissions related to titanium extraction, refining, and transportation. In CNC machining, although lower direct energy consumption per part is achieved, the high proportion of chips requires subsequent recycling or further processing, generating additional energy demand and environmental burden. The overall environmental advantage of each manufacturing approach depends on the scope of the assessment, particularly whether it considers only the energy consumption of the manufacturing equipment or the entire material-energy chain, including raw material sourcing, processing, and waste management [15].

4.2. Energy and Environmental Efficiency and Conditions for the Application of AM and CNC Technologies

In certain cases, additive manufacturing exhibits higher unit energy consumption of the equipment, as the energy required for material melting is substantial and a significant portion of the input energy is dissipated into the surrounding environment in the form of heat. Exergy analyses of SLM/DMLS processes indicate that only 6-10% of the input energy is directly utilized for part formation, while the remaining energy is lost as thermal energy. This effect is more pronounced in systems operating with higher laser power.

In powder bed fusion (PBF) systems with laser power levels of 300-500 W operating at full capacity for up to 20 hours per day, electricity consumption represents a significant environmental factor, particularly when the energy supply is based on fossil fuels [18].

In CNC machining, lower direct energy consumption per manufactured part is achieved, typically in the range of 3–7 kWh per implant. In additive manufacturing, energy consumption ranges from 15-35 kWh per implant when considering the operation of the manufacturing equipment alone. These values change when the energy associated with material waste and its subsequent recycling is considered. For example, the recycling of 0.55 kg of titanium chips, with a melting energy demand of approximately 20-30 kWh/kg, results in an additional energy consumption of 11-16 kWh. Consequently, the total energy balance of CNC machining approaches that of additive manufacturing. From an environmental perspective, CNC machining generates a higher volume of material waste requiring further processing [20].

From both practical and environmental perspectives, a threshold can be identified at which the preferred manufacturing technology changes. For small production batches (fewer than 100 units), additive manufacturing is generally considered more advantageous due to lower material waste, elimination of dedicated tooling, and reduced cumulative environmental impact in customized production.

For medium production volumes (100–1000 units), the decision is primarily influenced by geometric complexity: CNC machining is preferred for simpler geometries, while additive manufacturing is more suitable for complex, porous, or topologically optimized structures. In this case, the environmental balance depends on the trade-off between material waste and energy consumption. For large production volumes (more than 1,000 units), CNC machining is considered more energy-efficient on a per-part basis, particularly for geometrically simple components; however, material waste remains high, increasing the overall environmental footprint of the process [15].

The preferred manufacturing approach depends largely on the scope and assumptions of the sustainability assessment. The outcome varies depending on whether only the energy consumption of the manufacturing equipment is evaluated or whether additional factors are included, such as material efficiency, energy demand of material recycling, post-processing operations, and the source of electricity used in production. Consequently, environmental performance varies according to production conditions, process configuration, and energy sources.

Table 3 Practical scenarios for choosing between AM and CNC in the manufacture of dental implants

Terms and Conditions	Preferred technology	Explanatory statement
Highly complex geometry (porosity 30–50%, internal channels, microstructures)	AM (SLM/DMLS)	Complexity; CNC tool access limitations (e.g., channels 5 mm deep)
Small series < 100 pieces	AM (frequently)	Fixed steps: inert atmosphere + heating to 200–400 °C; the 30–45-minute duration is divided among the sections
Medium-volume runs: 100–1,000 units	It depends on the geometry	Simple shapes - CNC; complex/optimized - AM
Large production run > 1,000 units (e.g., 10,000 pieces)	CNC (frequently)	Consistent repeatability; accuracy of ±0.05 mm without finishing; AM may require additional steps for each part
Requirement for high accuracy ±0.05 mm	CNC	AM typically ±0.1 to ±0.2 mm; finishing may increase processing time by 10–30% and remove 0.1–0.5 mm per side

As shown in Table 3, it is evident that the suitability of additive manufacturing and CNC machining is not universal but depends on a combination of factors, including product geometric complexity, required dimensional accuracy, and production batch size.

Additive manufacturing is considered a more advantageous approach for the production of complex, porous, or topologically optimized implants, as well as for smaller production batches, where the fixed energy costs of the manufacturing process are distributed across multiple parts.

In contrast, for large-scale production of geometrically simpler components and in cases where high dimensional accuracy is required, CNC machining is regarded as the more suitable solution. The overall comparison of energy and environmental efficiency is also influenced by the inclusion of energy associated with the recycling of material waste generated during the manufacturing process.

5. Conclusion

The findings demonstrate substantial differences between additive manufacturing and CNC machining in terms of energy consumption, material efficiency, and environmental impact. Additive manufacturing enables the fabrication of complex and porous structures with high material efficiency and reduced material waste; however, this is achieved at the cost of higher energy consumption during the production process and subsequent post-processing operations. In contrast, CNC machining provides lower direct energy consumption per manufactured part and high dimensional accuracy but is associated with a significant proportion of material waste and additional energy demands related to its processing.

The results indicate that neither manufacturing technology can be considered universally superior from an environmental perspective. The suitability of each approach depends on the evaluation methodology, production batch size and geometric complexity of the implant. For small-batch and highly personalized production, additive manufacturing may represent a more sustainable approach under specific production conditions, whereas for large-scale production of geometrically simpler components, CNC machining is regarded as the more energy-efficient solution.

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