Title	Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: A life cycle approach
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Publication date	2021-01
Publication information	Lyons, Ronan, Anthony Newell, Pezhman Ghadimi, and Nikolaos Papakostas. “Environmental Impacts of Conventional and Additive Manufacturing for the Production of Ti-6Al-4V Knee Implant: A Life Cycle Approach.” Springer, January 2021. https://doi.org/10.1007/s00170-020-06367-7.
Publisher	Springer
Item record/more information	http://hdl.handle.net/10197/12734
Publisher's statement	This is a post-peer-review, pre-copyedit version of an article published in The International Journal of Advanced Manufacturing Technology. The final authenticated version is available online at: http://dx.doi.org/10.1007/s00170-020-06367-7
Publisher's version (DOI)	10.1007/s00170-020-06367-7

Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: A life cycle approach

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Abstract:

This paper explores whether additive manufacturing (AM) is more environmentally friendly than conventional manufacturing (CM) for the production of medical implants. The environmental impact of manufacturing the femoral component of a knee implant made from Ti-6Al-4V material was investigated. One AM method (electron beam melting (EBM)) and one CM method (milling) were analysed for the production of this part. A cradle to grave life cycle approach was utilised for each manufacturing method focusing on the primary energy consumption (PEC) and CO_2 emissions. It was found that when the entire life cycle of the implant is considered, EBM is a more environmentally friendly method of producing the implant. This is mainly due to the complex geometry of the implant. For complex geometries, lots of waste material is generated using CM processes, whereas much less material is wasted using the AM process. The production of the raw material, Ti-6Al-4V, has a high PEC and associated CO_2 emissions, so the amount of required raw material for either manufacturing method is the most important factor from an environmental perspective. Finally, the article presents the plans for future work and some remarks are concluded.

Keyword: additive manufacturing, conventional manufacturing, electron beam melting, machining, milling, LCA

Declarations

Funding

This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 16/RC/3872 and is co-funded under the European Regional Development Fund and I-Form industry partners.

Conflicts of interest/Competing interests

Not applicable

Availability of data and material (data transparency)

Not applicable

Code availability (software application or custom code)

Not applicable

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Published in: The International Journal of Advanced Manufacturing Technology, https://doi.org/10.1007/s00170-020-06367-7

1 Introduction

The manufacturing sector may include a very large and diverse group of businesses, however, as the impact of climate change is having a profound effect on the environment and future security, all significant manufacturing processes should be analysed for energy/carbon footprint to deduce whether improvements are feasible [1]. Recently, additive manufacturing (AM) technologies have been utilised for the production of various types of products with lower production volumes and products with high geometrical complexity [2]. Manufacturing activities are responsible for 19% of the world's greenhouse gas emissions. Therefore, many manufacturing companies view AM as a way to potentially reduce this effect [3]. The AM transformation and commercialisation have resulted in the global AM industry growing from a value of $0.4 billion in 1996 to being valued at $9.3 billion for 2018 and it is predicted to grow to almost $24 billion by 2022 [4].

Among the AM seven different categories defined by ISO/ASTM standards [5], Powder Bed Fusion (PBF) utilises a layer by layer part building mechanism using a thermal source. It sinters or melts metal or plastic powders depending on various applications. Selective Laser Sintering (SLS), Electron Beam Melting (EBM), and Selective Laser Melting (SLM) are three distinctive process categories in PBF technique. SLS, which is used to produce plastic parts, and SLM, which is used to produce metal parts, both use laser as their thermal source [6]. The EBM process uses an electron beam as its thermal source which results in many advantages when compared to laser-based processes, for example, less residual stress and less oxidation. EBM technique is a promising AM method that can produce entirely dense components employing an electron energy beam to melt powder layer upon layer [7].

In the global medical market, AM has the potential to provide competitive advantage with medical professionals increasingly realising the benefits AM can have on the medical industry [8-11]. In the medical device industry, creating patient-specific customised implants in fast turnaround time and a cost-efficient manner forms the main driver of using AM methods [9]. The ability of AM to produce geometrically complex parts is invaluable to surgeons as it allows them to make implants that exactly map to a patient's musculoskeletal structure [5]. Generally, complex manufacturing processes are required to produce orthopaedic implants, which help improve the quality of life of patients worldwide. As populations are ageing in developed countries, the number of artificial joint replacements required is likely to increase substantially [12]. Based on a recent report published by OECD [13], 182 hip replacement surgeries, per 100000 population, are done on average every year in the OECD32 countries with Germany at the top of the list with 309 surgeries per 100000 population. Regarding the knee replacements, on average 135 surgeries, per 100000 population, were accomplished in the OECD31 countries where Switzerland has the highest numbers of surgeries, 251. In Ireland, approximately 2,600 knee and 4,000 hip arthroplasties take place per year [14], with an increasing trend [13]. Typically, these implants are manufactured by utilising CM methods, which involve several energy-intensive processes, such as cutting, milling, electro-discharge processes, laser machining etc. However, this is just one stage of the lifecycle, the manufacturing process. If the entire lifecycle is considered in detail, there are numerous other energy expenditures and associated CO_2 emissions. Regarding the material properties, the Ti alloy, Ti_6Al_4V, is one of the most popular joint implant materials due to its biocompatibility, low density and strength [15]. Ti is a very expensive metal mainly due to the high specific energy consumption (SEC) of production in the long and demanding Kroll process which is a pyrometallurgical method implemented to produce metallic Ti from TiCl-4 [16].

From an environmental perspective, the material savings are possible when using AM technologies compared with CM [17]. Within this context, studies that provide comparative assessments of various manufacturing processes are highly important from the environmental and sustainability perspectives. These studies tend to highlight the environmental footprint of each manufacturing process by quantifying their energy use and greenhouse emissions [18]. Based on Priarone et al. [18], additive, subtractive and mass conserving processes form the three fundamental approaches in metal shaping. To highlight the potential of each approach, their environmental impact should be investigated in detail. Many studies to date have just considered the primary energy consumption (PEC) during the AM process or have not compared AM with CM in certain instances but instead compared different AM methods [19,20]. Hence, Table 1 presents an overview of the papers that have compared the environmental impacts of AM and CM.

Table 1 literature on the environmental impacts of AM compared with CM

Reference	Boundary	Product	Material	CM method	AM method
Paris et al. [2]	Manufacture to grave	Aeronautic turbine	Titanium	Milling	EBM
Faludi et al. [21]	Cradle to grave	Apple/linkage models	Acrylonitrile butadiene styrene (ABS)	CNC milling	FDM & Inkjet
Serres et al. [22]	Cradle to grave	Mechanical part	Ti-6Al-4V	Casting techniques	Laser-DED
Kreiger, Pearce [23]	Cradle to gate	Building block, waterspout, juicer	ABS and Polylactic Acid (PLA)	Injection moulding	FDM

Ingarao et al. [24]	Cradle to grave	Mechanical part	AlSi-10Mg	Machining and forming	SLS
Campatelli et al. [25]	Cradle to gate	Airfoil	EN S235JR structural steel	Hot rolling and machining	Wire arc additive manufacturing
Le, Paris [7]	Cradle to gate	Lightweight part	Ti-6Al-4V	Machining	EBM
Priarone et al. [18]	Cradle to grave	Mechanical part	Ti-6Al-4V	CNC lathe	EBM
Ingarao, Priarone [26]	Cradle to grave	Mechanical part	Ti-6Al-4V	Turning	EBM

Table 1 shows a list of publications for metal and polymer-based AM and CM methods compared using a lifecycle-based approach. Overall, there is still a need to quantify the environmental impacts of CM and AM processes and perform comparative analyses. Currently, only a few studies investigated the cradle to grave PEC and CO_2 emissions for functional parts made from Ti-6Al-4V. Besides, none of these studies compares the EBM additive process with the milling subtractive process for a functional medical implant. Therefore, the theoretical underpinnings of the current article aim to fill the identified gaps by;

(1) Comparing the environmental impact, considering PEC and CO_2 emission, of one AM method, EBM to that of a CM method, milling, for the manufacture of the femoral component of Ti-6Al-4V knee implants.

(2) Considering a cradle to grave boundary as the lifecycle scope of analysis. These lifecycle steps are (a) raw material extraction and preparation, (b) Ti alloy production, part manufacture including post-processing, and (c) recycling. As there is no relevant PEC during the use stage for the implant part this section stage has not been considered.

(3) Highlighting the areas along each lifecycle in which the PEC and CO_2 emissions are highest by presenting comprehensive process flow charts for each process step.

To address the aforementioned research aims, secondary data has been gathered to calculate the CO_2 emissions related to these two different types of manufacturing approaches based on the PEC. For the most part, the gathered data has come from the previous research literature. Where possible, for instance, when gathering data on a specific value, such as SEC of the Kroll process, the data had been gathered from as many high-quality secondary sources as possible, and then the average value was calculated to use in the life cycle assessment.

The remainder of this paper is followed by Section 2, where the life cycle assessment goal and scope are presented. Section 3 presents the life cycle inventory and calculation procedures. In

Sections 4 and 5, the lifecycle impact analysis is conducted and the results are discussed. Finally, some remarks are concluded in Section 6.

2 Goal and scope of the case study

The goal and scope of the study are split into sections including the definition of the functional unit, system boundaries, and assumptions of the study. The utilised life cycle approach in this study is in accordance with standards ISO 14040 and ISO 14041 [27] to measure the environmental impact of both AM and CM processes. Conducting this case study sheds light on the main elements and stages of the product life cycle that have major impacts on the environment in both studied processes.

2.1 The functional unit

The product under study is the femoral component of a typical knee implant made from the Ti alloy, Ti-6Al-4V. The function of the knee implant is to substitute the weight-bearing sides of the knee joint to ease pain and cure disability, which is commonly performed for patients suffering from arthritis [28,29]. The considered knee implant (the functional unit), shown in Fig. 1, is expected to allow the patient to have an 85-degree range of motion (5 degrees away from the straight knee and the ability to bend the knee back to 90 degrees) for 20 years. The dimensions shown in Fig. 2 have been used, which were derived from the knee implant design given by Sharma [30] to estimate the volume of material contained in a typical male femoral knee implant.

Fig. 1 The studied knee implant [30]

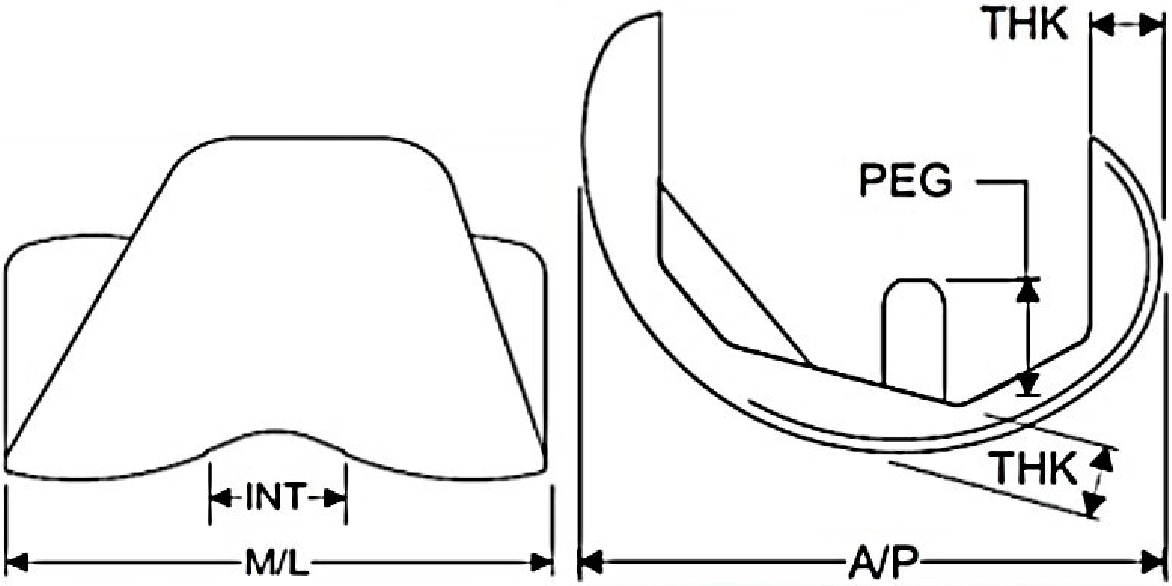

Fig. 2 The femoral component of a typical knee implant dimension [30]

The intercondylar notch (INT) is measured as 22 mm. The mediolateral (M/L) has a length of 80.6 mm. Two rectangular pegs (PEG) that each has a length of 13.7. The thickness (THK) of the implant is given at 9.4 mm. The anteroposterior (A/P) is measured as 76.6 mm. Using these measurements, the volume (V) of Ti-6Al-4V material contained in a finished femoral component is estimated to be approximately 4.48×10^{-5} m^3. The density (D) of grade 5 Ti-6Al-4V is approximately 4450 kg m^{-3} [31,32], the estimated mass is then approximately:

$$\text{Mass} = V \times D = 4.48\times10^{-5}\ (m^3) \times 4450\ (kg\ m^{-3}) = 0.2\ kg$$

Finally, the height (H) of the implant (from point touching the ground to the highest point) when placed in the position shown in Fig. 2 is 47.95 mm. Therefore, the envelope dimensions of the part are:

$$M/L \times A/P \times H = 80.6\ mm \times 76.6\ mm \times 47.95\ mm = 2.94 \times 10^{-4}\ m^3$$

This is equivalent to 1.3 kg of Ti-6Al-4V which is the minimum mass of the required workpiece for CM (milling). The calculated minimum mass value (1.3 kg) was obtained by multiplying the calculated envelope dimensions value of 2.94×10^{-4} m^3 to the density of grade 5 Ti-6Al-4V which is approximately 4450 kg m^{-3} [31,32]. The ratio of the build envelope to part, K, calculated as the minimum mass of the workpiece over the mass of the final part is 1.3 kg / 0.2 kg = 6.5. This is a very significant ratio for the analysis as it indicates the amount of waste material that will result from milling.

2.2 System boundaries

The life cycle is split into four distinct stages i.e. (1) raw material extraction and preparation (2) Ti alloy powder/workpiece production (3) part manufacture and post-processing (4) part recycling. The use phase is neglected as there is no significant associated PEC and CO_2 for this stage. Fig. 3 shows the four distinct stages, process flow, background processes and inputs under consideration.

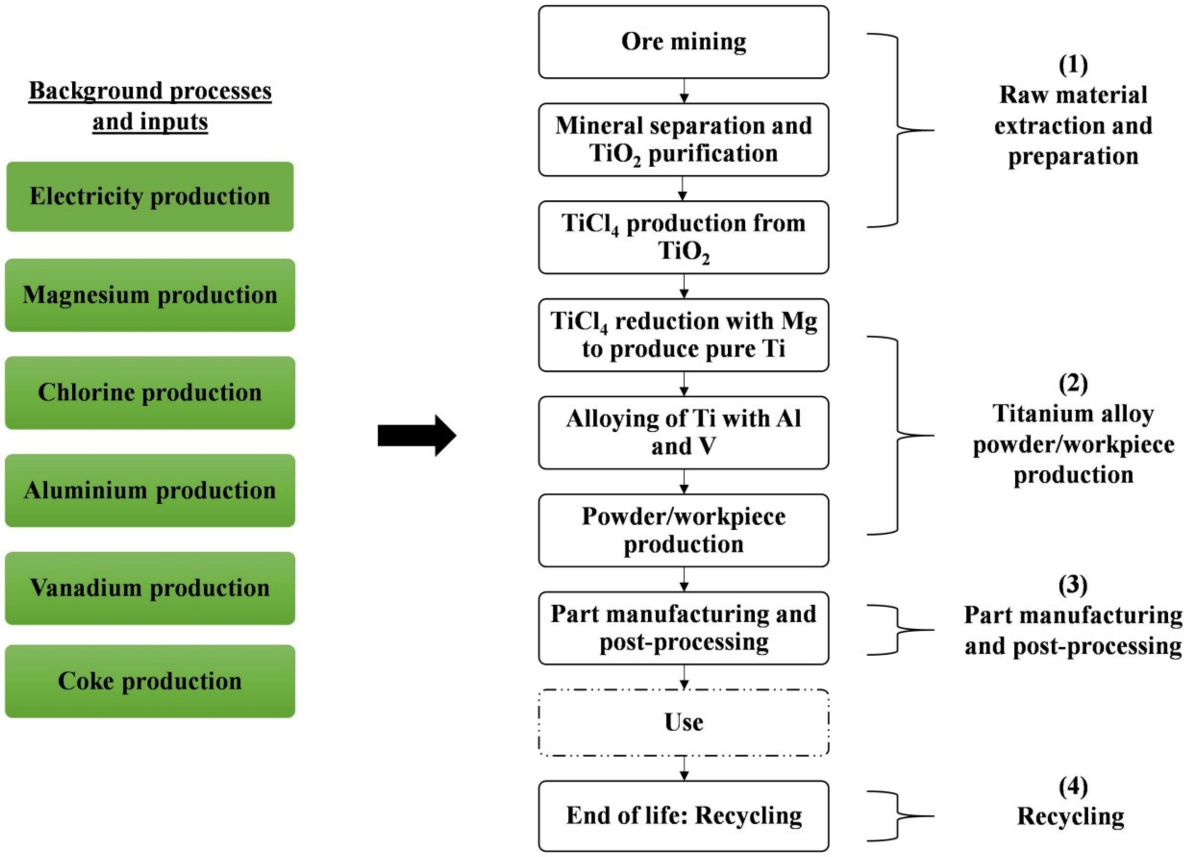

Fig. 3 Background processes and inputs, process flow and life cycle stages

Stage 1 (raw material extraction and preparation), stage 4 (recycling) and the first two steps of stage 2 ("TiCl-4 reduction with Mg to produce pure Ti" and "alloying of Ti with Al and V") are identical for both AM and CM processes. However, they are still included in this study as the results will be utilised in Section 5. It is worth to mention that the background processes and inputs part (highlighted in green) in Fig. 3 refers to the production of electricity and required materials in manufacturing the knee implant. The defined four stages of the system boundary are discussed in the following sub-sections.

2.2.1 Raw material extraction, preparation, and powder/workpiece production

Ti is the Earth's fourth most abundant structural metal [33]. The most important mineral sources are ilmenite ($FeTiO_3$) and rutile (TiO_2) [34]. In terms of natural reserves, rutile deposits are diminishing, while ilmenite deposits are abundant [34]. However, rutile mining is still more common than ilmenite mining. Australia has the largest reserves and production rate of rutile in the world. Ti ore is first mined and separated into rutile, ilmenite, leucoxene and other metal oxide impurities including iron oxide, zircon and monazite. The rutile is then separated from the other components by drum, electrostatic and magnetic separation [35].

The carbochlorination process then follows where TiO_2 in rutile is converted to $TiCl_4$ by reaction with chlorine and carbon in a fluidized bed of petroleum coke at ~900 ºC according to the following chemical reaction [36].

$$TiO_2 + C + 2\ Cl_2 \rightarrow TiCl_4 + CO_2$$

The gaseous $TiCl_4$ is then liquified and purified by distillation and stripping to remove other metal chlorides including vanadyl chloride, silicon tetrachloride and tin tetrachloride, finally resulting in a purity of +99.9%, which is important for obtaining a high-quality Ti metal which will be used for the Ti alloy powder/workpiece production. Today, despite the ongoing efforts of scientists and metallurgists to find a more environmentally friendly alternative, Ti is almost exclusively produced from $TiCl_4$ by the Kroll process. $TiCl_4$ is then reduced with molten magnesium at ~800 ºC, according to the following chemical reaction [36].

$$TiCl_4 + 2\ Mg \rightarrow Ti + 2\ MgCl_2$$

There is a large energy requirement for all stages of the process, particularly in melting Ti in a vacuum arc furnace (at 1670 °C) to produce Ti ingot. The alloying process to create Ti-6Al-4V then follows. There are a few different methods used for this alloying process though the most common method is vacuum arc re-melting (VAR) [37]. Finally, gas or plasma atomisation of the alloy to produce alloy powder is required for the AM process, and workpiece production is required for the CM process.

2.2.2 Part manufacturing and post-processing

The manufacturing processes are now split into the CM and AM methods for consideration individually.

- *CM method*

Milling is the most common machining process used for the rough manufacture of Ti alloy knee implants. However, there are usually several other processes required to produce an implant of correct dimension and surface finish after milling. Grinding is also common for post-milling finishing operations [38]. These material removal processes to produce a functional part from a Ti workpiece will be collectively referred to as machining. The first step is to convert the Ti-6Al-4V ingot into a workpiece of appropriate size. According to Paris et al. [2], a forging/rolling process is commonly utilised to produce the workpiece. Ti and its alloys are quite difficult to machine for the same reasons which make them functional in the body i.e. high strength and stiffness. Moreover, Ti work hardens during machining and has poor heat conductivity, leading to heat build-ups at the cutting edge and tool face [39]. As the production and the recycling of Ti are very expensive and energy-intensive, material waste is a big drawback to using CM approach.

- *AM Method*

One part of the AM process which is known to consume significant amounts of energy is powder production. There are several methods utilised for turning a Ti ingot into a Ti powder, which is suitable for AM. The main methods are gas atomization, plasma atomization, plasma rotating electrode and the hydride-dihydride process [40]. Gas atomization has been chosen to be considered in this study. In brief, during this process melted raw material flows through a nozzle due to the gravity effect. Argon jets are then used to split the melted material into fine droplets. The droplets then solidify due to a convective exchange taking place during their displacement in the atomization chamber [41]. EBM involves the successive selective melting and fusing of layers of metal powder to produce a part. This AM method is undertaken in a high vacuum chamber. Compared with SLM, EBM has a higher build rate due to the higher energy used and scanning method [42]. EBM technique is a promising AM method that can produce fully dense parts using an electron energy beam to melt powder layer by layer [7] and therefore has been chosen to be investigated in this study.

2.2.3 End of life recycling

As with most Ti products, removed Ti implants are usually melted down and recycled. Due to its high cost as well as its ability to maintain its mechanical and chemical properties after many uses, end-of-life (EoL) recycling rate of Ti is as high as 80% [43,44].

2.3 Assumptions and impact categories of this study

A cradle to grave approach is considered to incorporate the Ti recycling stage into the calculations. The following assumptions are made in this analysis:

1. The impact of transportation of all raw materials and the final functional unit will be neglected.
2. Rutile mining takes place in the New South Wales region of Australia.

3. All Ti will be produced using rutile as the raw material. No ilmenite use will be considered.
4. The manufacturing site for both AM and CM methods is in Texas.
5. There is no rework required for implants made by both AM and CM methods.
6. The impact categories considered at each stage for parts produced by either the AM or CM method will be the PEC and CO_2 only.

3 Life cycle inventory

For the life cycle inventory (LCI) stage of this study, the PEC and CO_2 outputs are presented for every stage (described in Sub-section 2.2) along the knee implant lifecycle. These values are first presented on a per kg basis and then on a per-part basis. The per kg values for AM indicate the amount of energy required to add 1 kg of material whereas, for CM, this is the energy required to subtract 1 kg of material.

3.1 LCI for raw material extraction and preparation

Australia has been chosen as the location for rutile mining as Australia has the largest reserves and production rate of rutile in the world [45]. Farjana et al. [46] calculated the total energy consumption associated with the mining of rutile in Australia. Stoichiometrically, 1.67 kg TiO_2 is required to produce 1 kg Ti. The rutile mining process has an SEC of 29.8 MJ/kg on a 1 kg Ti basis. In terms of CO_2 emitted per 1.67 kg of rutile produced, Farjana et al. [35] calculated value for CO_2 equivalent output to be 2.57 kg CO_2 on a 1 kg Ti basis. The typical rutile mining process is illustrated in Fig. 4.

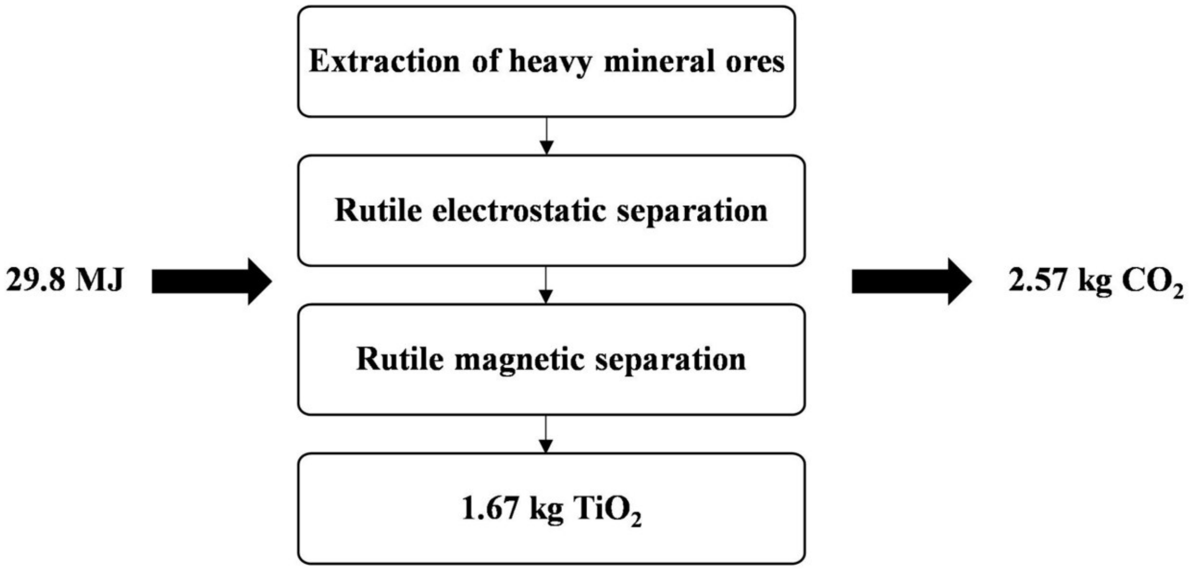

Fig. 4 Rutile Mining PEC and CO_2 output

3.2 LCI for titanium alloy powder/workpiece production

Fig. 5 illustrates the Kroll process with extra steps added for carbochlorination, alloying, atomization and workpiece production. Numerous values have been presented in the literature for the SEC of the Kroll process. Some of these values vary greatly from each other. However, the three values presented in Table 2 are the most accurate as they incorporate all process steps. By calculating an average of these three values, the SEC for the Kroll process is calculated as being approximately 445.74 MJ/kg.

Ancillary activities include activities, such as electricity production, which of course are important for this analysis. Gao et al. [47] calculated 28.19 kg CO_2/kg Ti for the CO_2 emissions associated with Ti production. They presented information for each stage of the process in their calculations resulting in an accurate assessment, therefore, their value has been considered for the CO_2 released during the Kroll process.

The carbon emission signature (CES) developed by Jeswiet, Kara [48] was used for calculating the CO_2 intensity of operations which uses electrical energy based on the carbon emissions signature of the power grid (Equation 1) of Texas, USA. In this equation, the conversion efficiency of electricity production is assumed to be 34%. %C, %NG, and %P, which are all fossil fuels, represent the percentages of coal, natural gas, and petroleum as the primary energy sources.

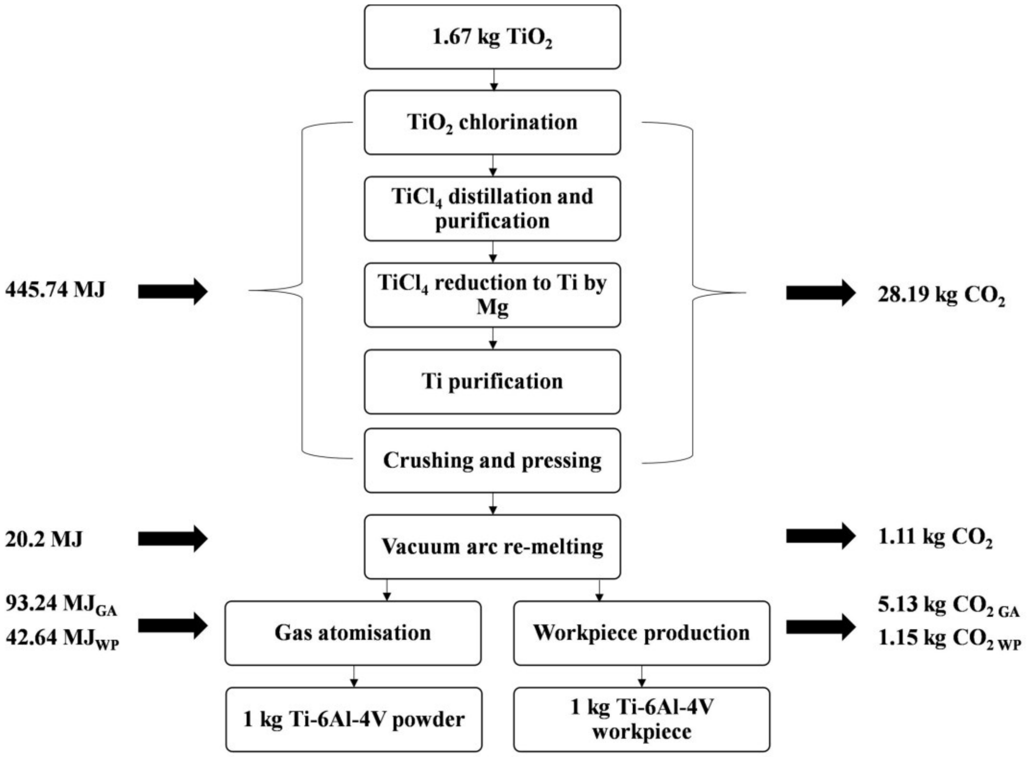

Fig. 5 Ti alloy powder/workpiece production PEC and CO_2 output

Table 2 Sources for SEC of Kroll process

Source	SEC (MJ/kg)
Yoshiki-Gravelsins et al. [49]	459.9
Forrest, Szekely [50]	424.8
Bravard et al. [51]	452.52

$$\text{CES} = \text{conversion efficiency} \times (112 \times \%C + 49 \times \%NG + 66 \times \%P) \quad (1)$$

The numbers 112, 49 and 66 represent the amount of CO_2 released when producing 1 GJ (gigajoule) of heat from each respective source. The CES for Texas can be calculated using Equation 2 and based on the Texas electrical power grid information for the percentages of coal and natural gas reported by Handy [52]. Based on Handy [52], petroleum is not a primary source of energy in Texas. Most of its primary energy sources consist of coal and natural gas and the rest are clean energy sources. Therefore, the value for %P is considered as zero in Equation 2.

$$\text{CES} = \left(\frac{100}{34}\right) \times [(112)(.36) + (49)(.3)] = 161.82 \text{ kg } CO_2/\text{GJ} \quad (2)$$

The resulting CO_2 emissions for the VAR alloying process has been calculated using this technique. The VAR process is used to join the Ti, Al, and V together to form the Ti-6Al-4V alloy. As reported by Muller, Weingarnter [53], this process consumes 6.87 MJ/kg of electrical energy. In PEC, this is 20.2 MJ/kg when the 34% electricity conversion efficiency is applied. The VAR process CO_2 emission is calculated as:

$$6.87 \times 10^{-3} \text{ GJ} \times 161.82 \text{ kg/GJ} = 1.11 \text{ kg } CO_2/\text{kg}$$

Similarly, the gas atomization process has been reported by Baumers et al. [54] to consume 31.7 MJ/kg of electrical energy, which is equivalent to a PEC of 93.24 MJ. Using the output of the CES technique (Equation 2), the associated CO_2 emissions attributed to gas atomisation is 5.13 kg CO_2/kg Ti-6Al-4V alloy powder.

$$31.7 \times 10^{-3} \text{ GJ} \times 161.82 \text{ kg/GJ} = 5.13 \text{ kg } CO_2/\text{kg}$$

The material processing phases up to VAR is the same for CM. The difference is that instead of atomization, forging of the ingot is used to create a suitable workpiece. The cylindrical workpiece is created by a combination of forging and rolling which according to Ashby [55] has a SEC of 14.5 MJ/kg, PEC of 42.64 MJ/kg, and CO_2 emissions of 1.15 kg·CO_2/kg.

3.3 LCI for part manufacturing and post-processing

Published in: The International Journal of Advanced Manufacturing Technology, https://doi.org/10.1007/s00170-020-06367-7

The PEC and CO_2 emissions associated with the AM and CM processes are analysed separately in the following sub-sections.

3.3.1 AM and post-processing LCI

The EBM process, shown in Fig. 6, includes the final post-process finishing operations, which are required for medical implants. Baumers et al. [54] have calculated the electrical energy consumed per kg of deposited material during EBM as 59.96 MJ. As before, using an electricity conversion efficiency of 34%, the PEC for EBM is 176.35 MJ/kg. Huang et al. [17] measured CO_2 emissions from the Arcam A1 (EBM system) to be 4.1–12 kg·CO_2/kg when working with Ti-6Al-4V. For a component of a similar mass and geometry as the femoral knee implant, Priarone et al. [18] calculated the CO_2 emissions for the Arcam A1 to be 11.62 kg.CO_2/kg when working with Ti-6Al-4V. A value of 9.7 kg CO_2/kg is obtained using the output of the CES technique using Equation 2.

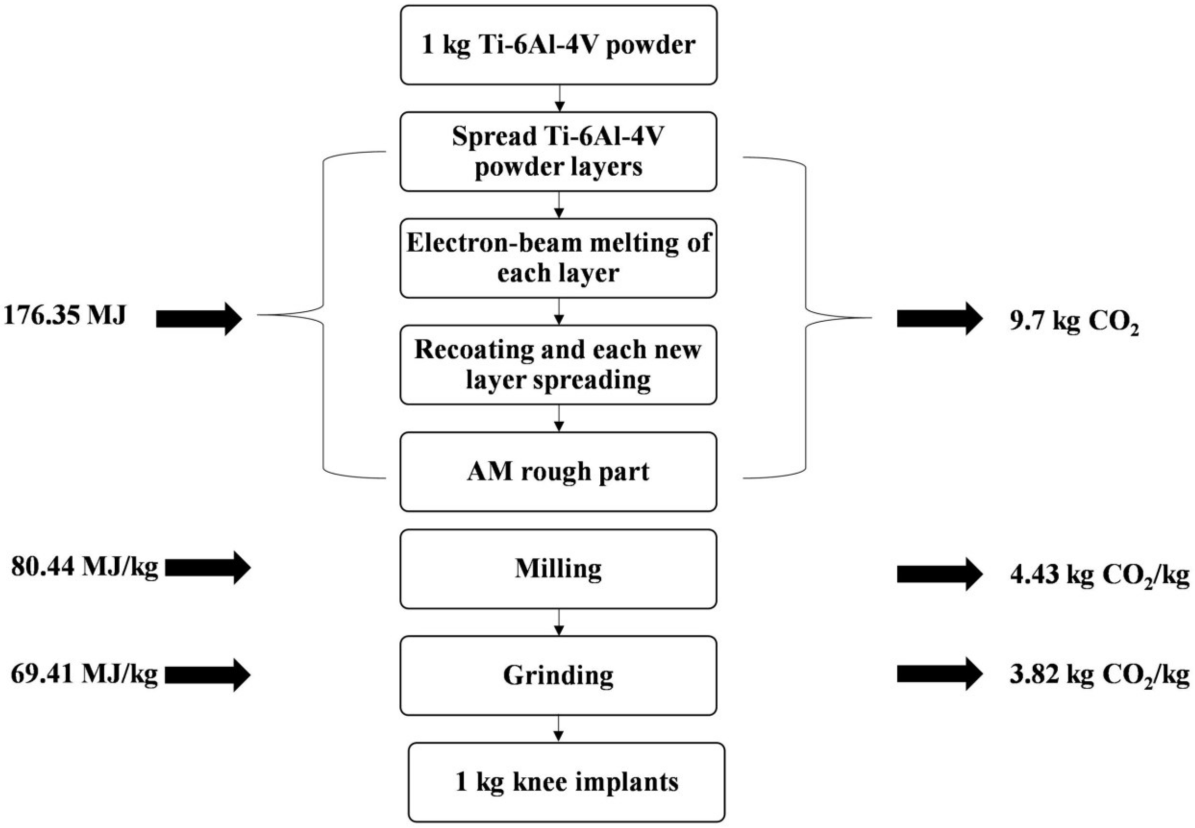

Fig. 6. EBM PEC and CO_2 output.

As discussed, post-processing is required to obtain a sufficiently good surface quality after EBM due to the rough surface finish of the as-produced AM part. Commonly used post-processing techniques include milling followed by grinding which has been considered for this paper. Using the CES technique, a value of 80.44 MJ/kg for PEC and a value of 4.43 kg·CO_2/kg has been calculated for the CO_2 output. Using a grinding depth of 0.02 mm and a feed rate of 6 m/min, Guo et al. [56] calculated the specific grinding energy for grinding Ti-6Al-4V to be 23.6 MJ/kg, PEC 69.41 MJ/kg. Using the CES method, 3.82 kg CO_2/kg was obtained for grinding. Fig. 6 depicts all the calculated PEC and CO_2 for the EBM and post-processing milling and grinding processes.

3.3.2 CM and post-processing

A wet CNC milling process is used for CM of the knee implant, the process for which is shown in Fig. 7. It is assumed that the Mori Seiki Dura Vertical 5500 CNC milling machine is used [57]. Kara, Li [58] proposed an empirical model for assessing the SEC of milling and turning processes based on the material removal rate (MRR) shown in Equation 3. In this case, the SEC is the amount of energy consumed when the milling tool removes 1 cm^3 of material. Kara, Li [58] established Equation 3 for the SEC for wet milling on the Mori Seiki Dura Vertical 5500.

$$\mathrm{SEC} = 2.953 + 2.019/\mathrm{MRR}\ (\mathrm{kJ/cm^3}) \qquad (3)$$

The material removal rate for milling can be calculated using Equation 4 [7]:

$$\mathrm{MRR} = \frac{axial\ depth\ of\ cut\ \times\ radial\ depth\ of\ cut\ \times\ cutting\ feed\ \times\ feed\ per\ tooth\ \times\ number\ of\ teeth}{60\ \times\ \pi\ \times\ Diameter\ of\ Cutting\ Tool} \qquad (4)$$

In the current study, roughing is carried out using a 15 mm diameter flat end mill followed by finishing using an 8 mm diameter flat end mill. Table 3 tabulated the considered values for axial depth of cut, radial depth of cut, cutting feed, feed per tooth, and number of teeth extracted from **Le, Paris [7]**.

Table 3 Cutting conditions for milling

Element	**Roughing**	**Finishing**
Axial depth of cut (mm)	2.5	0.25
Radial depth of cut (mm)	11.25	6
Cutting feed (m/min)	40	60
Feed per tooth (mm/tooth)	0.075	0.07
Number of teeth	4	4
MRR (cm^3/s)	0.119	0.017
SEC (kJ/cm^3)	19.72	121.72
SEC Electrical (MJ/kg)	4.47	27.35
SEC (Primary) (MJ/kg)	13.15	80.44

These values have been used in Equation 3 to arrive at an SEC for roughing equalling to 4.47 MJ/kg and a SEC for finishing to be 27.35 MJ/kg. This equates to 13.15 MJ/kg and 80.44 MJ/kg PEC, respectively. Using the CES techniques in Equation 2, for Texas, a value of 0.72 kg CO_2/kg for roughing and 4.43 kg CO_2/kg for finishing have been obtained. Next, the effects of grinding on SEC have been studied. As investigated by Guo et al. [56], using a grinding depth of 0.02 mm and a feed rate of 6 m/min, the specific grinding energy for Ti-6Al-4V was calculated to be 23.6 MJ/kg.

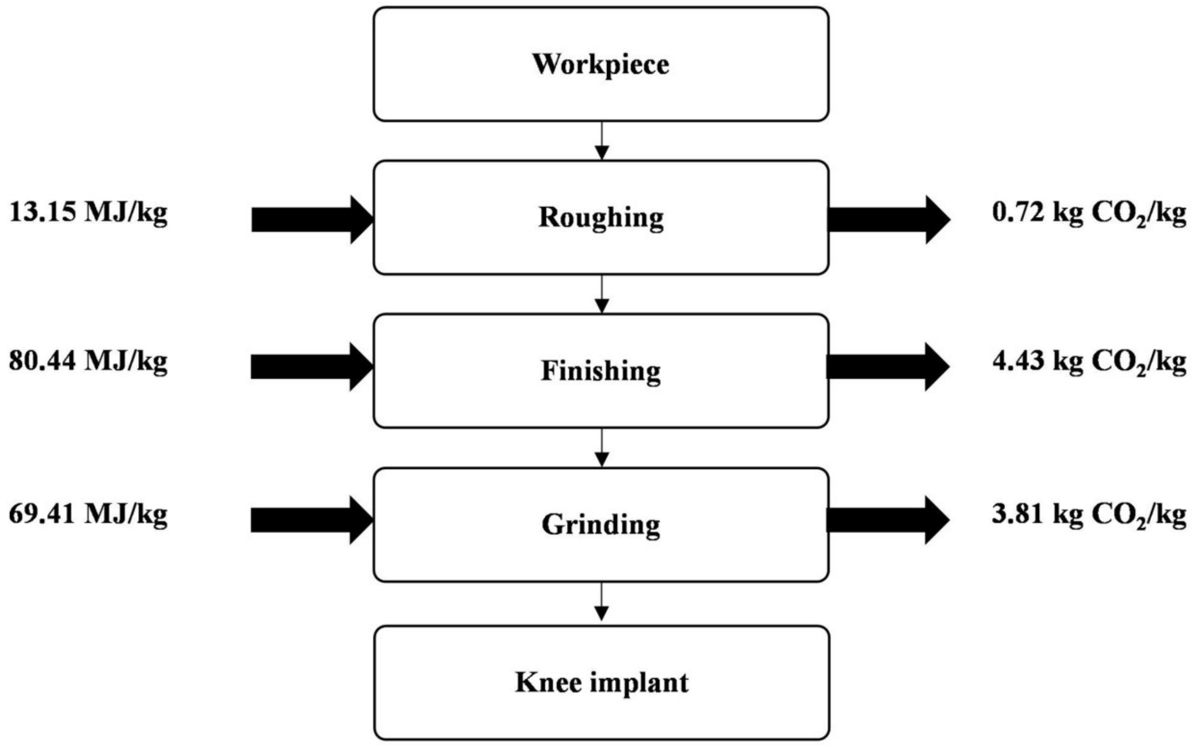

Fig 7 CM for knee implant PEC and CO_2 output

The PEC is then 69.41 MJ/kg and 3.81 kg·CO_2/kg output. The PEC for polishing and cleaning is negligible, so they are not considered in this analysis.

3.4 End of life recycling

The typical process for Ti recycling is shown in Fig. 8. This is a very important point to note as the estimated embodied energy for primary production of Ti-6Al-4V is 685 MJ/kg compared with an estimated embodied energy of 87 MJ/kg for recycled Ti-6Al-4V [55]. Further to this, according to Ashby [55], the CO_2 output is 5.2 kg·CO_2/kg recycled Ti. These values include all processes involved in the recycling stage.

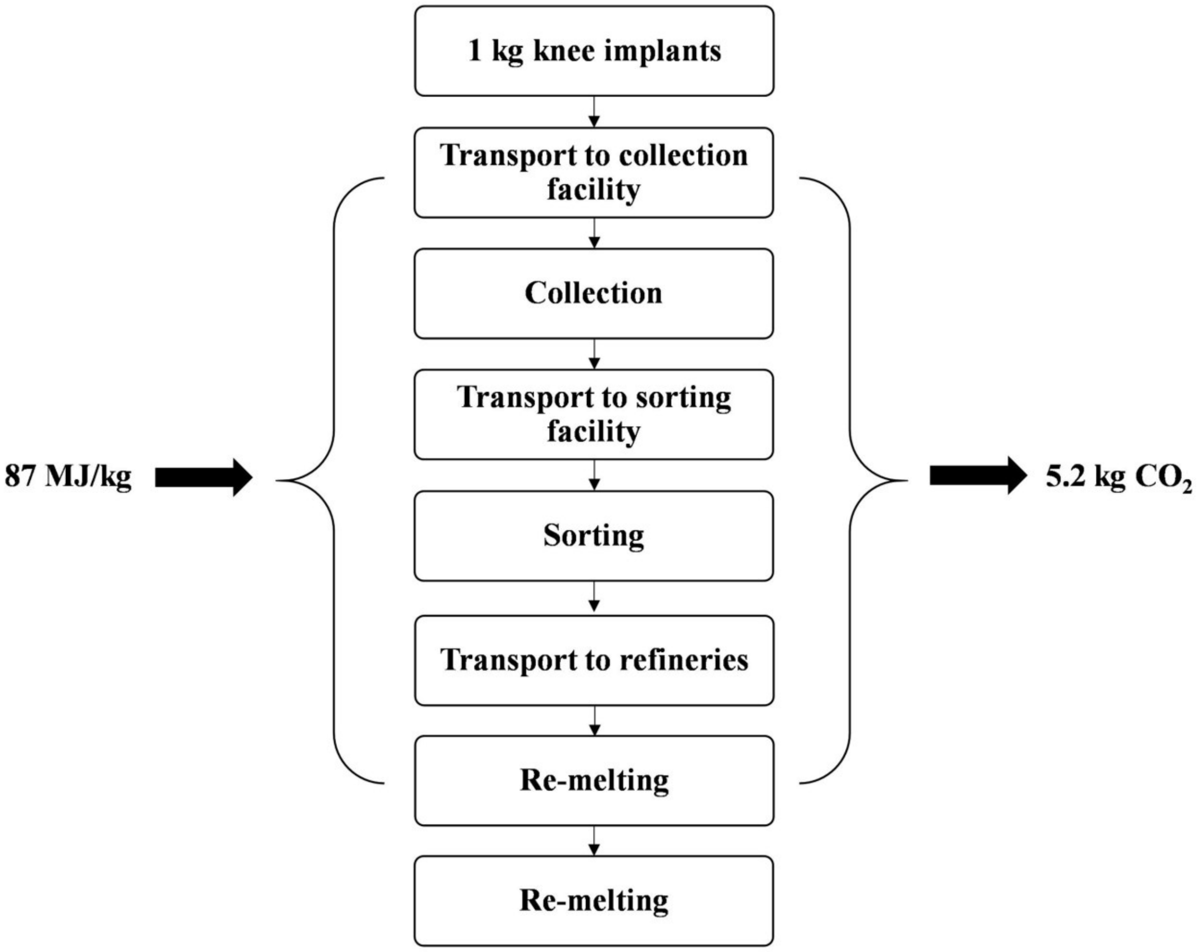

Fig. 8 Process for Ti Recycling PEC and CO$_2$ output

4 Life cycle impact assessment

4.1 Per part PEC for AM

The embodied energy necessary to produce a Ti-6Al-4V ingot when recycling has been considered (E_E), can be calculated using Equation 5 [18]:

$$E_E = E_V - r \times (E_V - E_R) \tag{5}$$

Where E_V is the embodied energy for the primary production of Ti-6Al-4V ingot, r is the end of life recycling rate, and E_R is the embodied impact of recycled Ti-6Al-4V. Inputting the calculated values in Sections 3.1 and 3.2 of $E_V = 475.54$ MJ/kg (Rutile mining + Ti production), $r = 0.8$, and $E_R = 87$ MJ/kg in Equation 5 gives a value of 164.71 MJ/kg for E_E. The next step is to calculate how much Ti-6Al-4V material is required for the EBM process when considering material losses due to post-processing. Equation 6 allows to estimate this value:

$$M^{AM} = m_p + m_a \tag{6}$$

M_p is the weight of the part that must be obtained, 0.2 kg. m_a is the machining allowance for post-processing. Rännar et al. [59] estimated that approximately 1 mm of extra material should be added to all surfaces as an allowance for post-process machining. Based on this statement, a value of approximately 35% of M^{AM} has been estimated for the allowance. This value was checked against those calculated by Priarone et al. [18], where they used the same principle to estimate allowances for three parts of different size and geometry. Their values ranged from 13% to 46% depending on geometrical complexity, which is consistent with the estimation used here. Using these values, the value of M^{AM} has been calculated to be 0.31 kg, consisting of 0.2 kg for m_p and 0.11 kg for m_a.

Now, the total amount of energy required to produce the Ti-6Al-4V powder necessary for the implant can be calculated using Equation 7.

$$E_{mat} = M^{AM} \times (E_E + E_{Pr}) \qquad (7)$$

E_{Pr} is the energy necessary to further process the material into powder using gas atomization, 93.24 MJ/kg. Therefore, based on Equation 7, E_{mat} can be calculated to be 79.96 MJ.

Next, the per part PEC (E_{EBM}) is calculated for the EBM manufacturing process (Equation 8) by multiplying the calculated M^{AM} to the obtained PEC for EBM process in Sub-section 3.3.1 (176.35 MJ/kg).

$$E_{EBM} = M^{AM} \times PEC_{EBM} = 0.31 \text{ kg} \times 176.35 \text{ MJ/kg} = 54.67 \text{ MJ} \qquad (8)$$

Next, the energy necessary for finishing operations (milling + grinding) needs to be calculated. As discussed in Sub-section 3.3.1, milling followed by grinding is required in order to remove excess powder and to make sure that all dimensional specifications have been precisely adhered to. The PEC for milling is approximately 80.44 MJ/kg and for grinding is 69.41 MJ/kg. As already discussed, 35% (0.11 kg) is the allowance for post-process machining, 30% (.093 kg) of this will be for milling and 5% (.016 kg) for grinding. Therefore:

$$E_{milling} = 0.093 \text{ kg} \times 80.44 \text{ MJ/kg} = 7.48 \text{ MJ} \qquad (9)$$

$$E_{grinding} = 0.016 \text{ kg} \times 69.41 \text{ MJ/kg} = 1.11 \text{ MJ} \qquad (10)$$

Table 4 summarizes the presented calculations in this section and tabulates the total PEC for AM method per part which is 143.22 MJ/part.

Table 4 Total PEC for AM

Process Step	**PEC (MJ/part)**

Production of Ti-6Al-4V powder	79.96
EBM	54.67
Post-process milling	7.48
Post-process grinding	1.11
Total	**143.22**

4.2 Per part CO_2 Emissions for AM

The CO_2 emissions for the production of the Ti-6Al-4V powder are approximated by adding the CO_2 emitted per part for the production of the ingot from rutile ore to the CO_2 emitted per part for atomization. The total emissions are calculated by (2.57 + 28.19 + 1.11 + 5.13) × 0.31 = 11.47 kg CO_2 for a 0.31 kg part before finishing based on the available information in Sections 3.1, and 3.2. Next, the CO_2 emissions for the EBM process must be calculated by multiplying the specific CO_2 emissions for EBM (9.7 kg CO_2/kg) by M^{AM} (0.31) which gives a value of 3 kg CO_2. Post-process milling emits 4.43 kg CO_2/kg, therefore given the machining allowance of 0.093 kg, the associated emissions for this process are 0.41 kg CO_2. For post-process grinding, which emits 3.82 kg CO_2/kg, using the machining allowance of 0.016 kg yields 0.06 kg CO_2. Table 5 summarizes the presented calculations and tabulates the total CO_2 emissions for the AM method per part which equates to 14.94 kg/part.

Table 5 Total CO_2 emissions for AM

Process Step	**CO_2 emissions per part (kg/part)**
Production of Ti-6Al-4V powder	11.47
EBM	3
Post-process milling	0.41
Post-process grinding	0.06
Total	**14.94**

4.3 Per part PEC for CM

The first calculation that must be made for CM is the amount of workpiece material required. Equation 11 is used to calculate this value [18]:

$$M^{CM} = M_p + M_C \text{ (kg/part)} \tag{11}$$

Where M_p is the mass of the part to be obtained, 0.2 kg. M_C is the mass of the milled chips. The minimum mass of the workpiece is obtained at 1.3 kg. However, it is important to add 5% extra to this value for material losses that may occur when converting the ingot into a workable billet. Therefore, M^{CM} equals to 1.37 kg consisting of 0.2 kg for the part (M_p) and 1.17 kg of milled chips (M_c). Next, the total PEC needed for the production of the workpiece is calculated using Equation 12 [18]:

$$E_{mat} = M^{CM} \times (E_E + E_{PR}) \quad (12)$$

E_{PR} (energy for forging and rolling the material into a workpiece) is equal to 42.64 MJ/kg. Therefore, E_{mat} is equal to 284.07 MJ/kg considering the calculated E_E in Section 4.1. Next, the proportion of the 1.17 kg of the used machined chips are estimated as 80% (0.94 kg) for roughing, 17.5% (0.2 kg) for finishing and 2.5% (0.029 kg) for grinding. Therefore, the PEC for each of these processes is:

Roughing = 0.94 kg × 13.15 MJ/kg = 12.36 MJ

Finishing = 0.2 kg × 80.44 MJ/kg = 16.08 MJ

Grinding = 0.029 kg × 69.41 MJ/kg = 2.01 MJ

Table 6 summarizes the presented calculations and tabulates the total PEC for the CM method per part which is calculated as 314.52 MJ/part.

Table 6 Total PEC for CM

Process Step	**PEC (MJ/part)**
Production of Ti-6Al-4V workpiece	284.07
Milling	28.44
Grinding	2.01
Total	**314.52**

4.4 Per part CO_2 Emissions for CM

The CO_2 emissions for the production of the Ti-6Al-4V workpiece are calculated by adding the CO_2 emitted per part for the production of the ingot from rutile ore and the CO_2 emitted per part for forging/rolling (2.57+ 28.19 + 1.11 + 1.15) x 1.37 = 45.24 kg CO_2/part. Next, the CO_2 emissions for the roughing process must be calculated by multiplying the specific CO_2 emissions for roughing (0.72 kg CO_2/kg) by the machining allowance for roughing (0.94 kg), which results in 0.68 kg CO_2. For finishing, the same calculation process is followed, which arrives at 0.89 kg CO_2. The post-process grinding process emits 3.81 kg CO_2/kg. For the 0.029 kg of material used for grinding, 0.11 kg CO_2 is calculated. Table 7 summarises the presented calculations and tabulates the total CO_2 emissions for the CM method per part which is 46.92 kg/part.

Table 7 Total CO_2 emissions for CM

Process Step	**CO_2 emissions per part (kg/part)**

Production of Ti-6Al-4V workpiece	45.24
Roughing	0.68
Finishing	0.89
Post-process Grinding	0.11
Total	**46.92**

5 Comparisons and discussion

5.1 Primary energy consumption comparison

Fig. 9 illustrates the PEC comparison between an identical femoral knee implant manufactured using the CM and AM methods. The part manufactured by CM methods consumes well over double the PEC than the part manufactured using the AM method, EBM at 314.52 MJ and 143.22 MJ, respectively. However, if all other processes are ignored and we focus solely on the manufacturing processes (including post-processing), EBM consumes almost double the PEC of CM.

The production of workable Ti-6Al-4V material is the biggest consumer of energy in each case. Producing the required amount of powder for AM is 28.1 % of the PEC to produce the billet in CM. This is mainly due to the significantly larger amount of material required for machining. AM requires just 22.6 % the amount of material required for an identical part manufactured using CM. The amount of material required for CM is directly related to the geometrical complexity of the part.

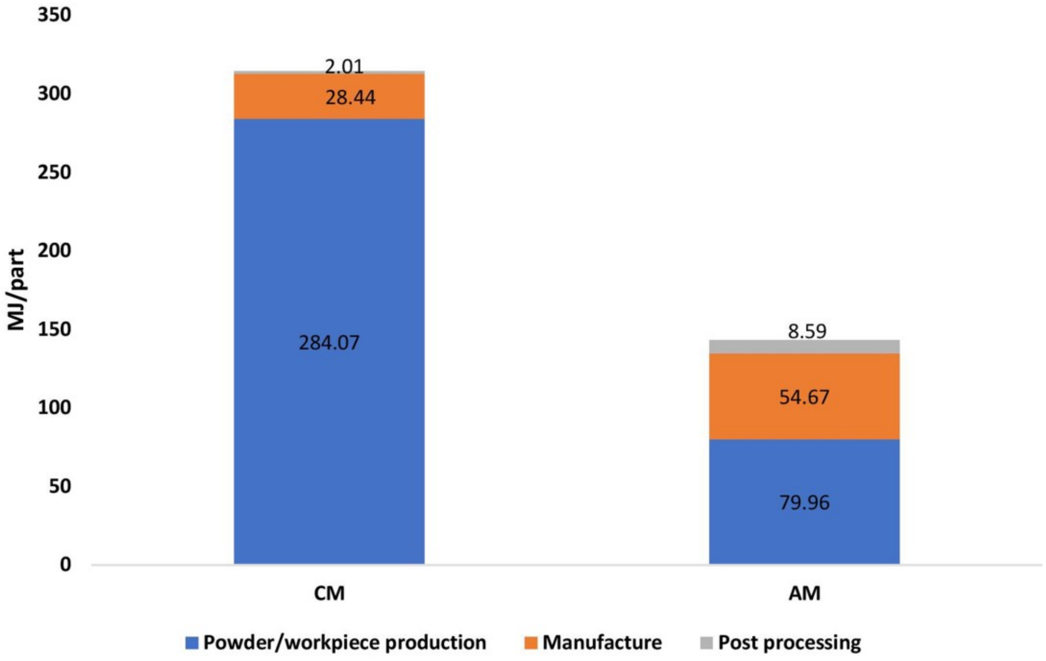

Fig. 9 AM vs CM PEC per part

For AM, the amount of waste material will never be more than 50% and is usually 10-40% of the total mass of material required. For the implant that is the focus of this study, 84.6 % of material must be subtracted from the billet to make the final part for CM. This is wasted Ti-6Al-4V, which must now be converted from machined chips back into a usable form. This compares with only 35% of material waste for the implant manufactured using AM. At 475.54 MJ/kg, Ti-6Al-4V has one of the highest embodied energies of any material. Therefore, from an environmental perspective, the material should be used as efficiently as possible. CM does not use material efficiently, especially for complex geometries such as knee implants.

Fig. 9 further shows how much of the embodied energy of a Ti-6Al-4V implant is the result of producing the Ti-6Al-4V billet. At 284.07 MJ out of a total 314.52 MJ, workpiece production is responsible for a very significant 90.3% of the embodied energy for the implant manufactured by machining. When the AM process is considered, it is much less than for the machining process due to the more efficient Ti alloy utilisation. For the AM process, in particular, Ti-6Al-4V powder production is responsible for 55.8% of the total PEC.

5.2 CO_2 emissions comparison

Fig. 10 compares the CO_2 emissions per part for manufacturing using CM vs. AM. CM is 3.94 times higher than AM at 45.24 kg·CO_2 and 11.47 kg.CO_2, respectively. The impact of the workpiece production for CM has an even more dominant impact than it had on PEC, being responsible, almost entirely accounting for it with 96.4 % of the total CO_2 emissions.

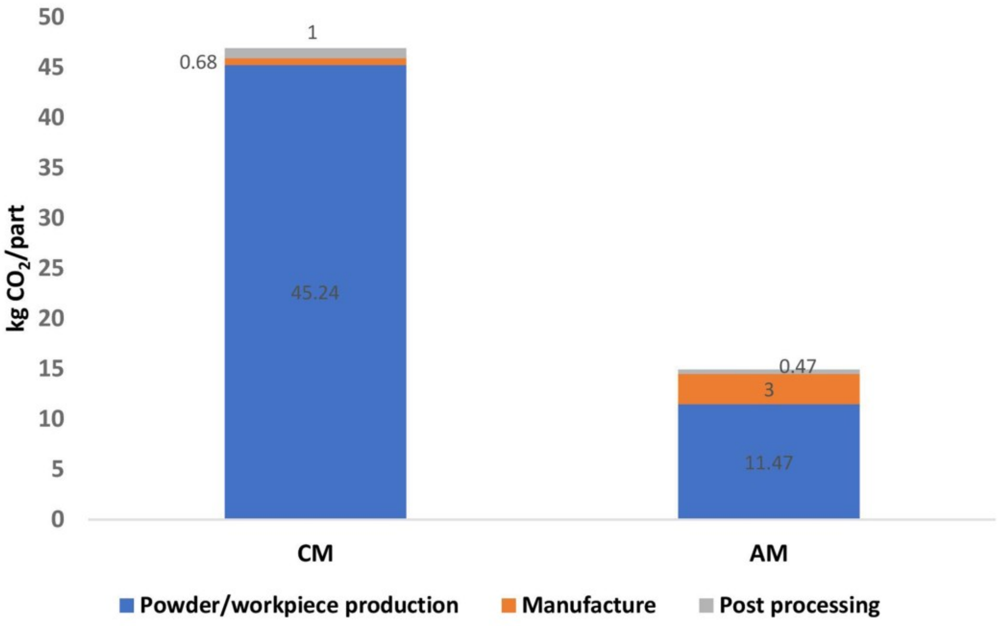

Fig. 10 AM vs CM CO_2 outputs per part

As shown in Fig. 10, the production of the Ti-6Al-4V powder for AM accounts for 76.8% of the total CO_2 emissions. It is interesting to observe that if the focus is solely on the manufacturing stage (including post-processing), then EBM's CO_2 emissions are 2.07 times that of CM.

5.3 Discussion

The theoretical and practical underpinnings of this research work lay in performing a detailed comparative environmental analysis of the AM and CM processes for producing a femoral component of Ti-6Al-4V knee implant. It was found that the main reason for the differences in the PEC and CO_2, when the AM and CM processes are compared for making the same knee implant, is the huge amount of waste material generated for the CM process. Only 15% of the workpiece mass for CM is utilised in the final part, whereas for AM it is 65%. Even though the AM Ti alloy powder feedstock is more energy-intensive to produce, its vastly greater material utilisation provides a significantly improved PEC and CO_2 for the AM knee implant.

It was found in this paper that the geometric complexity of the part has a large influence on the material wastage when CM is considered vs. AM for the same part. Lian et al. [60] and Sun, Lian [61] developed a novel convexity measurement for 3D meshes calculated by minimizing the ratio of the summed area of valid regions in a mesh's six views, which are projected on faces of the bounding box whose edges are parallel to the coordinate axes, to the sum of three orthogonal projected areas of the mesh. Based on these works, Fera et al. [62] presented a new part complexity index capable of measuring the multi-level aspects of complexity in manufacturing processes. The authors of the present paper plan to develop a part geometric complexity model that considers a series of additional factors. This model will integrate a new operational complexity and new part complexity indices. It will investigate the AM and CM processes with the goal of forming a model that correlates the dimensional deviation with part characteristics such as volume, number of dimensions, a geometrical complexity index, and process parameters. This concurrent consideration will increase the accuracy of the environmental analysis comparisons.

On top of the environmental analysis aspects, it should be noted that the proposed approach could be extended to consider simultaneous environmental and economic sustainability comparisons, which will lead to more informed decisions. Recently, Ingarao, Priarone [26] compared the energy demand and life cycle cost of the turning process with EBM. A few of the most important cost elements considered in their analysis were purchase cost of metal powder, labour costs for the AM machine, and cost of electric energy. The CM cost items were workpiece purchasing cost, cost of the cutting tool and fluid, and cost of energy. It was concluded that the AM process provided better energy demand for the considered case study. Furthermore, the AM process production costs per part has been calculated to be at least twice as much as the CM process. In the future work, it is aimed to perform a lifecycle techno-economic assessment of both AM and CM methods while extending the presented environment analysis in the current paper. This will be done in conjunction with integrating a geometric complexity model discussed in the previous paragraph.

6 Conclusion and future works

Based on the findings of this research, EBM is a more environmentally sustainable manufacturing process for the studied knee implant, largely due to the geometric complexity of the part, as determined by the small fraction of the minimum bounding box which the part material occupied. This high geometric complexity led to poor material utilisation for CM and a large amount of wastage. Parts with simpler geometries as determined by a larger fraction of part material occupying the minimum bounding box would, therefore, be better suited for CM due to greater material utilisation. AM is a less desirable option for parts with low geometric complexity and therefore similar material utilisation comparing to CM. An identical implant can be manufactured by EBM using just 22.63% the amount of material required for CM. Furthermore, the implant made by EBM has a 45.5% lower PEC and releases 31.8% the amount of CO_2 of its CM counterpart. This research work shows that from an environmental perspective, parts with high geometric complexity such as femoral knee implants are more suited to AM than CM. However, the notion of complexity will need to be further explored with the incorporation of other factors, such as production planning constraints, performance, engineering design and manufacturing costs.

Apart from the environmental analysis and as mentioned in Sub-section 5.3, integrated geometric complexity and techno-economic models need to be developed in the future in order to provide simultaneous economic and environmental sustainability analyses in more detail. This will support decision making for industrial practitioners and designers to find environmental and economic optimal routes for manufacturing a given product using either AM or CM or a combination of both. As this study compared the PEC and CO_2 emissions, future work could involve a more complete life cycle assessment of AM metal parts production when other inventory data becomes available to more adequately compare AM and CM. Further to this, if the femoral implant part were redesigned to take advantage of AM unique capabilities utilising, for example, topological optimisation, without compromising on functionality, this could provide a more suitable comparison with the CM part design instead of using geometrically identical parts.

Acknowledgements

This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 16/RC/3872 and is co-funded under the European Regional Development Fund and I-Form industry partners.

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Published in: The International Journal of Advanced Manufacturing Technology, https://doi.org/10.1007/s00170-020-06367-7